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Love-wave biosensors using cross-linked polymer waveguides on $LiTaO_3$ substrates

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The design and performance of Love-wave sensors using cross-linked poly-(methyl methacrylate) waveguides of thickness of 0.3 – 3.2 μm on $LiTaO_3$ substrates are described. It is found that this layer-substrate combination provides sufficient waveguidance, and electrical isolation of the IDTs from the liquid environment to achieve low acoustic loss and distortion. In bio-sensing experiments, mass sensitivity up to 1420 Hz/(ng/mm^2) is demonstrated.

Introduction: Acoustic wave-based sensors have been widely investigated and used for the detection of hazardous compounds in gas environments [1]. More recently, acoustic wave devices have received considerable attention for applications in liquid-phase detection [1–4]. Various types of acoustic waves are being studied, including thickness shear mode (TSM), shear horizontal acoustic plate mode (SH-APM), shear horizontal surface acoustic wave (SH-SAW), and flexural plate wave (FPW).

Of all acoustic wave devices, SH-SAW devices appear most promising for (bio-)chemical detection in liquid environments. However, despite their structural similarity to Rayleigh waves, SH-SAWs often propagate slightly deeper within the substrate [5], hence preventing the implementation of high

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sensitivity detectors. The subject of this letter is the guided SH-SAW sensor (also known as Love-wave sensor), which is particularly suitable as a high sensitivity detector in liquids. It consists of an SH-SAW device with an overlayer having a lower shear wave velocity. The effect of the overlayer is to trap the acoustic energy near the sensing surface [5], thus increasing the sensitivity to surface perturbations. If appropriately selected, the overlayer will also provide electrical passivation of the interdigital transducers (IDTs) and protection against chemicals in the liquid.

Various dielectric materials such as silicon dioxide (SiO_2), silicon nitride (Si_3N_4), and most polymers can be used as the waveguide material. Polymers have an advantage over other waveguide materials for Love-wave sensor implementation due to their relatively low shear wave velocity and the ease of surface layer preparation. However, because of their viscoelasticity, cross-linking is necessary to avoid excessive acoustic loss [1]. Cross-linking allows the acoustically lossy polymer to exhibit an equilibrium elastic stress, thus representing a stable waveguide layer. Therefore, careful choice of waveguide material, thickness, and pretreatment is needed, in addition to general design parameters for acoustic wave sensors like IDT geometry and substrate material.

Devices: The Love-wave sensor consists of an SH-SAW device on 36°YX-$LiTaO_3$ with a poly(methyl methacrylate) (PMMA) waveguide. The device is fabricated with 100 nm thick Cr/Au IDTs having a period of 40 μm, which corresponds to an operating frequency of approximately 103 MHz. A dual delay line configuration is used with a metallized delay path to eliminate acoustoelectric interaction with the load. The PMMA waveguide layers were deposited on the device surface (over the IDTs and the delay path) by spin coating solutions of 10% and 20% w/v PMMA (35000 g/mole) in 2-ethoxyethyl acetate. The polymer layer was then cross-linked by heating it to 180°C for 2 h. Depending on concentration and spin speed, waveguide thicknesses of approximately 0.3 – 3.2 μm have been obtained, as determined by profilometry.

Biochemical Preparation: The sensors were cleaned for 60 min in 0.1M HCl. Next, one delay line (reference line) was blocked by applying a solution of 10 mg bovine serum albumin (BSA) in 1 ml tris(hydroxymethyl)-aminomethane buffer for 60 min. Finally, both delay lines were exposed to a solution of 10 μg goat immunoglobulin G (IgG) in 1 ml phosphate buffered saline (PBS) for 60 min. Each step was followed by rinsing in PBS.

Results and Discussion: Several devices with waveguide thicknesses ranging from 0 to 3.2 μm have been characterized. The insertion loss as a function of waveguide thickness is shown in fig. 1 for three different boundary conditions (the entire coated surface exposed to air, DI water, and PBS, respectively). Note the overall loss can also be lower, depending on the degree of cross-linking. This occurs when the spin-coated polymer is placed immediately in the oven already at 180°C, as opposed to ramping the oven temperature from 30°C to 180°C for 15 minutes. From fig. 1, the loss in air increases sharply starting near 2.0 μm. If the PMMA overlayer is too thick (over 2.5 μm), the acoustic attenuation becomes large, indicating that over-confinement of the wave to the interface will increase the coupling to the liquid medium. This, together with the PMMA absorbing a small amount of water [6], results in increased insertion loss for water loading. On the other hand, already a thin polymer layer (less than 1.0 μm) effectively isolates the IDTs electrically from the liquid, a fact which in part can be attributed to the high dielectric constant of $LiTaO_3$ ($\varepsilon_r = 47$). (It is noted that for quartz substrates with $\varepsilon_r = 4.5$, electrical isolation of the IDTs imposes a more serious problem [6].) However, such a thin polymer layer does not efficiently trap the acoustic energy near the sensing surface. Thus, a compromise in waveguide thickness must be made, combining a high sensitivity with a moderate loss. For our sensor design, the optimum waveguide thickness is approximately 2.0 – 2.3 μm.

Fig. 2 shows the response of goat IgG covered Love-wave devices to injection of 24 μg/ml rabbit anti-goat IgG for different waveguide thicknesses. The difference signal (sensing line minus reference line) is shown. It is obvious that mass sensitivity increases with waveguide thickness, while differences in baseline noise are small.

In order to determine the mass sensitivity of the Love-wave devices, two quartz crystal microbalances (QCMs) were treated in the same manner as the sensing lines of the Love-wave sensors, and the same biochemical reaction was performed. Using the Sauerbrey equation, these experiments revealed a mass density of the deposited rabbit anti-goat IgG layer of 17 ng/mm^2, corresponding to a closely-packed monolayer of antibodies. This result was then used to calibrate the Love-wave sensors, indicating that mass sensitivities up to 1420 Hz/(ng/mm^2) have been measured. This value must be compared to the baseline noise level in order to estimate the detection limit of the devices. Note the detection limit is defined as three times the peak-to-peak noise [3] or three times the root mean square (rms) noise [6].

Because the phase is measured using a signal generator and a vector voltmeter, the experiments are designed to obtain a maximum amount of information rather than to minimize the noise. However, in an attempt to further reduce the noise, the data collection software was modified for the detection of small antibody concentrations by averaging the data taken over a period of 5 minutes: Fig. 3 shows the detection of 100 ng/ml rabbit anti-goat IgG by a 1.57 μm thick waveguide device. In this experiment, the dispense order of BSA and goat IgG adsorption was reversed, since this resulted in a better suppression of non-specific antibody adsorption on the reference line. Noise levels of 32 Hz (peak-to-peak) and 8 Hz (rms) have been obtained. These results reveal the most sensitive device can detect 68 pg/mm^2 or 17 pg/mm^2, respectively, the latter corresponding to 0.1% of a close-packed monolayer of antibodies.

It was found that cleaning the device with a swab stick soaked in ethanol, the sensors can be used a number of times with excellent reproducibility.

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Figure captions:

Fig. 1: Insertion loss as a function of waveguide thickness for Love-wave sensors operated in the indicated media.

● air

■ DI water

◆ PBS

Fig. 2: Response of Love-wave sensors with waveguides of the indicated thicknesses for binding of a monolayer of antibodies. The antibody was injected after 10 min.

■ 0 nm

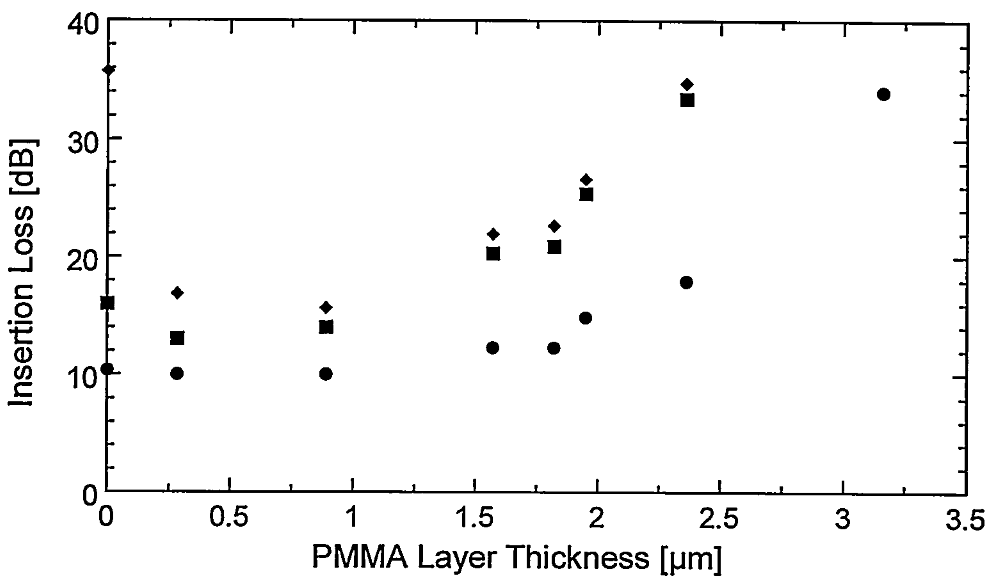
▼ 890 nm

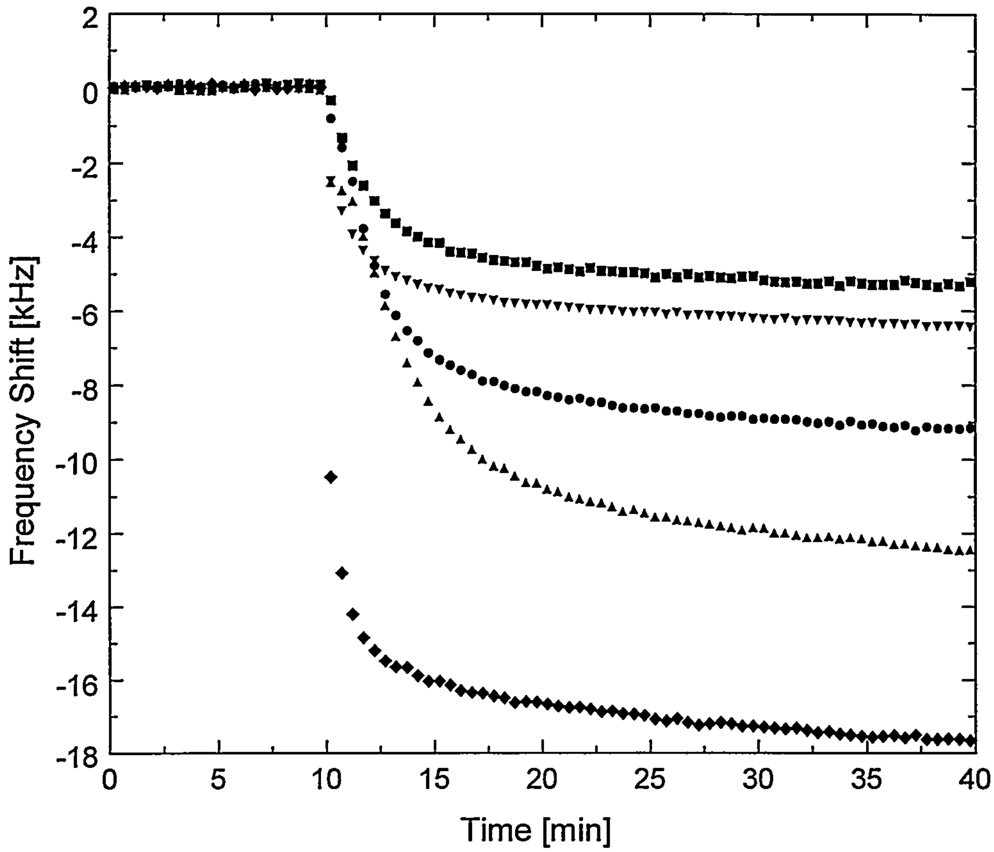
● 1570 nm

▲ 1820 nm

◆ 1950 nm

Fig. 3: Detection of 100 ng/ml antibody, injected after 15 min, by a Love-wave device using a 1.57 μm thick PMMA waveguide.


40
30
20
10
0
Insertion Loss [dB]
0
0.5
1
1.5
2
2.5
3
3.5
PMMA Layer Thickness [μm]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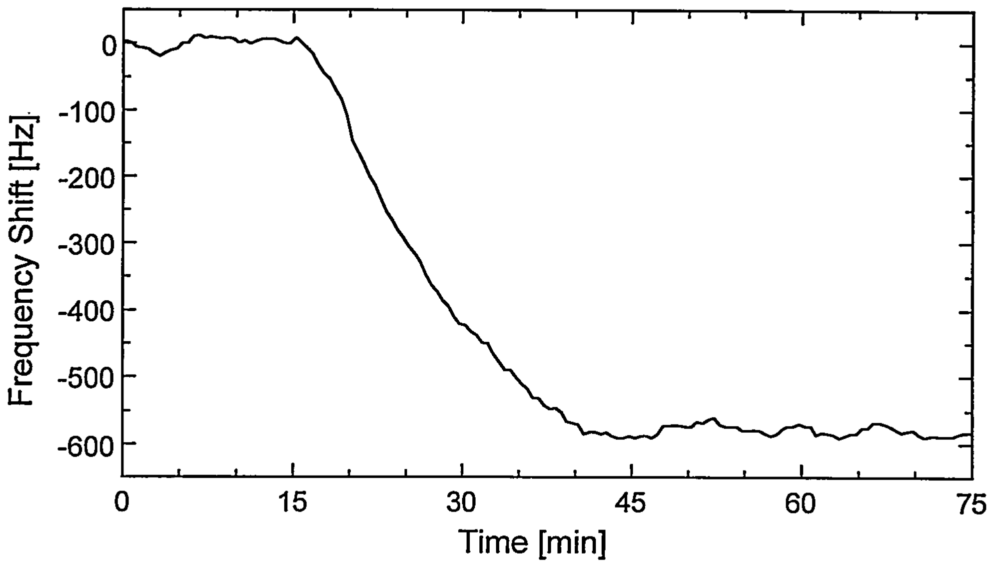

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