High-frequency One-port Colpitts SAW Oscillator for Chemical Sensing

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***Abstract*—This paper reports upon the design and development of a low cost, high sensitivity, high frequency surface acoustic wave resonator (SAWR) based system for gas sensing applications. The 262 MHz one-port SAWR operates in a grounded-base Colpitts oscillator arrangement that was developed based on an equivalent circuit model. Electrical characteristics of the fabricated SAWR show good agreement with its equivalent device model at the resonant frequencies, and it was found to have good stability and sensitivity with a Q-factor in air of about 2,870 at its fundamental resonant frequency. The sensor system is designed to operate in a dual configuration in which one resonator is coated with a gas-sensitive polymer (polyethylene) coating, whilst the second one is used as a reference channel; thereby eliminating common mode interferences on the baseline signal. Mass sensitivity was found to be ca. 1 Hz/ng, which corresponds to sub-ppm sensitivity to gas/odour concentration.**

Keywords-acoustic waves; one-port; Colpitts oscillator; BVD model; SAW resonator;polymer coating

I. INTRODUCTION

Both bulk acoustic and surface acoustic wave (SAW) based sensor systems have been reported in chemical sensing applications over the past few decades [1–4]. Due to their high sensitivity and simple drive/readout circuitry, more recent focus has been on surface acoustic wave based devices where a SAW device forms the frequency selective component within an oscillator circuit. Polymer-coated SAW based chemical sensors impart high sensitivity and selectivity to specific volatile compounds. The absorption of the ligand molecule onto the polymer changes the physicochemical and electrical behavior of the SAW device resulting in a change in its oscillation frequency.

Common methods to implement SAW oscillator circuits are typically based on the feedback loop method or the negative resistance method [5], [6]. The frequency stability and vapor sensitivity of the SAW sensor system directly depends on the type of the employed oscillator circuit. Nimal *et al.* [7] have recently reported that one-port Colpitts oscillators are more sensitive, but less stable, than two-port Pierce oscillators. The sensitivity can also be improved by tuning the phase point set within the SAWR in the pass band thereby reducing the noise performance of the oscillator circuit [8].

In this study, we present one-port polymer-coated Rayleigh wave based SAW resonators, fabricated on an ST-cut quartz wafer, for application in low-cost chemical sensors. An investigation into different equivalent circuit models is also presented, which lead to the conclusion that the most suitable oscillator circuit for one-port SAWR sensors is a Colpitts oscillator configuration.

II. ONE PORT SAW RESONATOR

SAW resonators are commonly available as one-port and two-port devices employing either delay line or resonator configurations. Because of the potential for high Q-value, low noise level and higher stability, we have selected a one-port resonator structure. These resonators are designed to operate at a baseline frequency of 262 MHz in a dual configuration to obtain differential measurements (Fig. 1).

The design and modeling of surface acoustic devices are normally carried out using the well-established Coupling of Modes (COM) theory [9], [10]. Although a COM model allows for an accurate description of the SAW resonator by simulating the admittance behaviour, the formulas are somewhat cumbersome and are not very informative - as far as circuit analysis and simulation is concerned. In addition, the accuracy of this model is limited to a narrow frequency band around the resonance region. Hence, the COM theory must assume *near-resonance* frequencies in order to derive a simplified electrical model of the SAW resonator [11].

The Butterworth Van Dyke (BVD) model, as a simple electrical equivalent circuit model, is more suitable for circuit designers. Morgan [12] established that the electrical acoustic impedance behavior of a SAW device, obtained using a lumped-element equivalent circuit model, is in good agreement with conventional COM analysis. This equivalent circuit model conveniently relates the acoustic perturbations due to surface mass loading in a SAW device to its electrical behavior.

A BVD model [11] was developed for the 262 MHz one-port SAWR, shown in Fig. 2., allowing quick simulation and design of the associated oscillator circuitry. The motional and static arm parameters were extracted using the transmission parameters of the SAWR. As shown in Fig. 2, the electrical components R, L and C are the motional inductance, capacitance and resistance respectively, which form the *motional arm* producing the resonant frequency while the capacitor C_o forms the *static arm* providing the anti-resonant frequency. The motional arm signifies the electro-acoustic properties [13] of the piezoelectric material and it models the vibration of the crystal. R represents the acoustic attenuation in the resonator and capacitance C_o the capacitance of the piezoelectric crystal.

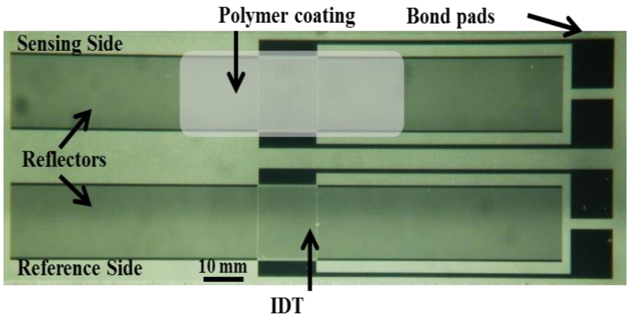

Fig.1. Optical micrograph of the 262 MHz one-port dual SAW resonator sensor, fabricated in aluminium on a ST-cut quartz wafer substrate. The top resonator is coated with a chemically-sensitive non-conductive polymer (polyethylene) and the bottom resonator is uncoated thus acting as a reference channel.

The designed 1-port SAWR comprises 60.25 finger pairs with 3 µm finger width forming the inter-digitated-transducer (IDT), and 500 reflectors on each side to create a standing wave pattern with an overall die size of 7.4 mm × 2.4 mm. The dual resonator configuration [14] with a reference channel eliminates common mode interferences on the baseline signal, such as changes in ambient temperature or pressure. The SAWRs were fabricated on an ST-cut quartz substrate with aluminum IDTs using UV lithography (PacTech, Germany).

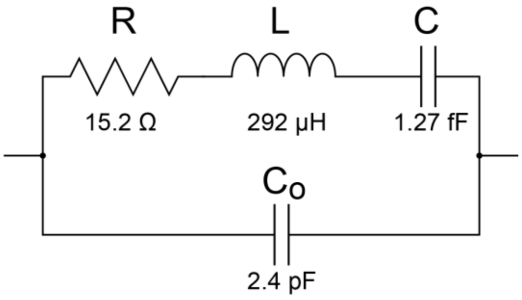

Fig.2. Illustration of the BVD equivalent circuit lumped element model of a one-port SAW resonator.

In addition to the fundamental mode of operation, the SAWR exhibits several overtone frequencies, which can be modelled by adding additional series-resonant branches to the BVD model. For operation around a certain resonant frequency, the crystal can be modelled by the circuit with a single motional arm. The impedance of this modelled circuit is given by [15]:

$$Z(s)=\frac{s^2+\left(\frac{R}{L}\right)s+\omega_s^2}{sC_o\left[s^2+\left(\frac{R}{L}\right)s+\left(1+\frac{C}{C_o}\right)\omega_s^2\right]} \tag{1}$$

where

$$\omega_s=2\pi f_s=\frac{1}{\sqrt{LC}}, \tag{2}$$

$$f_s=\frac{1}{2\pi\sqrt{LC}} \tag{3}$$

Here, f_s is the series resonance frequency of the SAWR, modeled by the motional arm. The unloaded quality factor of a SAWR is given by

$$Q_u=\frac{\omega_s L}{R} \tag{4}$$

Due to the high Q-factor of a SAWR, R can be neglected. Thus (1) becomes,

$$Z(s)=\frac{s^2+\omega_s^2}{sC_o\left[s^2+\left(1+\frac{C}{C_o}\right)\omega_s^2\right]} \tag{5}$$

This shows that the resonator exhibits a parallel resonance at:

$$f_a=\frac{1}{2\pi\sqrt{LC_T}} \tag{6}$$

where

$$C_T=\frac{CC_o}{C+C_o} \tag{7}$$

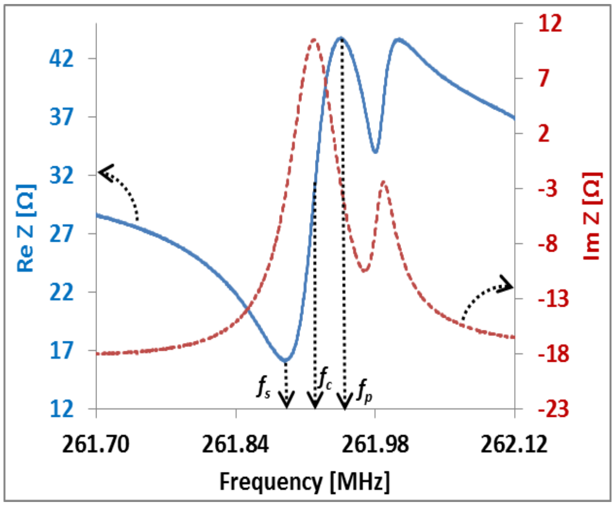

Fig.3. Real (Solid line) and imaginary parts (dotted line) of the impedance presented by 262 MHz one-port SAWR. The series, parallel and center frequencies are marked on the diagram.

The real and imaginary parts of the one-port SAWR impedance exhibiting a minimum resistance at resonance and a maximum resistance at anti-resonance frequencies, obtained by an RF network analyzer (E5071B, Agilent Technologies), is shown in Fig. 3. The series resonance frequency, f_s, is 261.91 MHz, the parallel resonance, f_a is 261.94 MHz and the center frequency, f_c is 261.92 MHz. This also demonstrates that the SAWR center frequency lies as expected between the series and parallel resonant frequencies. The phase curve in Fig. 3 also shows that the Barkhausen criterion of 0° phase condition for oscillation is satisfied at the center frequency of the SAWR.

III. COLPITTS OSCILLATOR DESIGN

Several similar transistor-based circuit configurations are available for the realisation of SAW oscillators, such as Pierce, Colpitts, and Clapp, with the main difference lying in the transistor grounding options. The performance of the three configurations varies with the difference in the position of the biasing resistors and capacitances. The most desirable option is the Pierce configuration due to its simplicity, robustness and ability to work at higher frequencies (> 500 MHz) because it is arguably the least affected by stray capacitances [15]. However, the Pierce oscillator can only work with a two-port SAW resonator within a feedback loop to attain the required 180° phase shift.

The Colpitts oscillator, however, allows the SAWR to operate in a 1-port configuration [7], and therefore was selected for this work. The schematic of the Colpitts SAW oscillator circuit with a grounded base configuration, where the SAWR input is connected to the transistor's base and the output port is connected to the ground, is shown in Fig. 4.

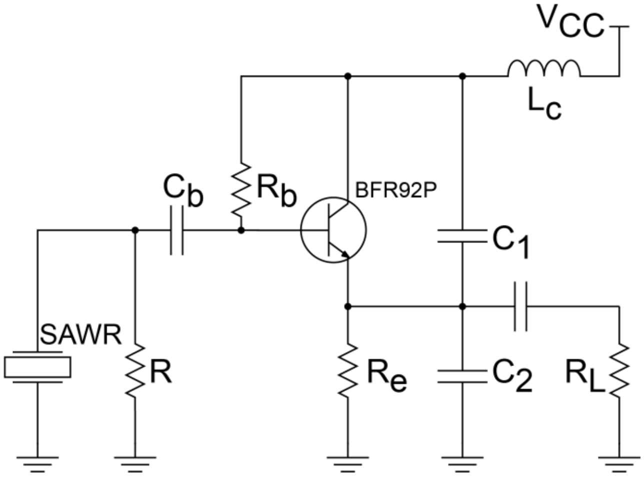

Fig. 4. Simplified schematic of the Colpitts oscillator circuitry used to drive the 1-port SAW resonator sensor.

The Colpitts oscillator offers good stability at higher frequencies, lower harmonics, lower component count and hence lower cost than other types including feedback-based oscillator. The transition frequency of the transistor, f_T , limits its frequency of operation, when the capacitors needed for obtaining the oscillation frequency are comparable to the transistor's terminal capacitances. This may be avoided by using a high f_T value (a few gigahertz) BJT in the oscillator circuit or by using the crystal in a series resonance configuration [15]. The use of RF transistor (BFR92P, Infineon) rather than an operational amplifier also reduces parasitic capacitances allowing radio frequency (RF) oscillator operation. To obtain the tuned oscillation frequency close to the SAWR Q-factor, tight tolerance components were selected for the capacitor and the inductor values.

In this configuration, the resonator shows an inductive behavior between the series (f_s) and parallel resonances (f_p). The transistor along with the feedback capacitors C_1 and C_2 provides the negative resistance to compensate for resistive losses in the resonator. The major limitation of such an oscillator circuit is that the parasitic capacitances begin to affect the effective operation of the circuit at frequencies above 500 MHz.

IV. CHEMICAL DETECTION SYSTEM SETUP

A robust, high-sensitivity chemical detection system based on polymer-coated one port SAW sensor has been designed and implemented. The SAW oscillator has been realized by interfacing the dual SAW resonators to Colpitts oscillator circuitry. A two layered Printed Circuit Board (PCB) has been designed using Altium Designer software. Figure 5 shows the photograph of the dual Colpitts SAW oscillator based chemical sensor system. The PCB ensures minimal cross-talk associated with high frequency signals. The phase shifts linked with the RF signal paths to the resonators have also been taken into account during the PCB design.

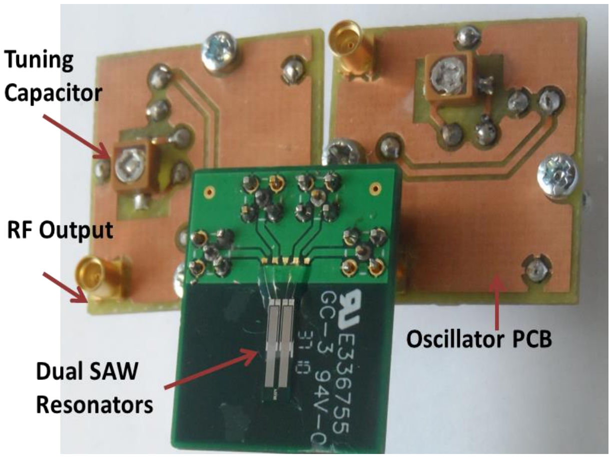

Fig.5. Photograph of the SAW resonator with associated Colpitts oscillator circuit on the backside of a custom PCB.

The experimental arrangement demonstrating chemical detection using SAWR oscillator consists of a 14×14×40 cm^3 gas/odor chamber (photograph of the setup is shown in Fig. 6) to which a neMESYS multi-channel syringe pump (Cetoni GmbH, Germany) is attached. The microliter precision syringe delivers the chemicals into the chamber via capillary lines, where it gets vaporised. The SAW sensors, arranged in dual configuration, where one is coated with the sensing polymer *polyethylene* and the other sensor forms the reference channel are attached to the far end of the chamber. A commercial FQ4 interface instrument (JLM Innovation, Tubingen, Germany) was connected to the oscillator output for frequency measurement. The oscillation frequencies of the individual sensors were monitored to obtain the SAWR differential signal.

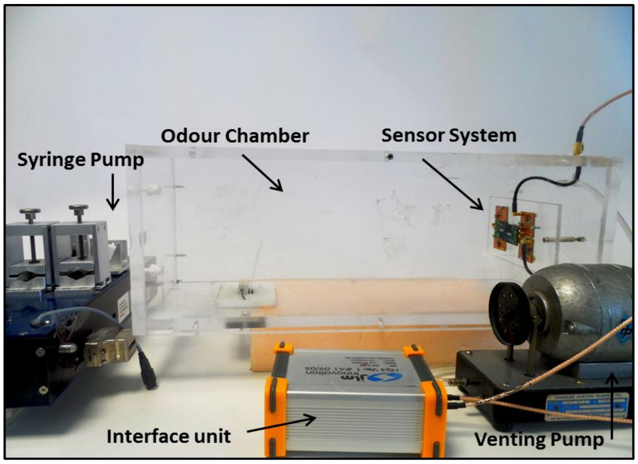

Fig.6. Experimental arrangement for chemical detection sensor system consisting of an odour chamber, a venting pump, syringe pump, and SAW sensors with the Colpitts circuitry.

V. EXPERIMENTAL RESULTS

Figure 7 shows the oscillator's resonant frequency output obtained by an RF oscilloscope (LeCroy LT342 Waverunner). The measured frequency value is in good agreement with the theoretically modeled value. The load sensitivity is significantly less for this oscillator circuit. The output of the SAWR oscillator is practically noise and distortion free.

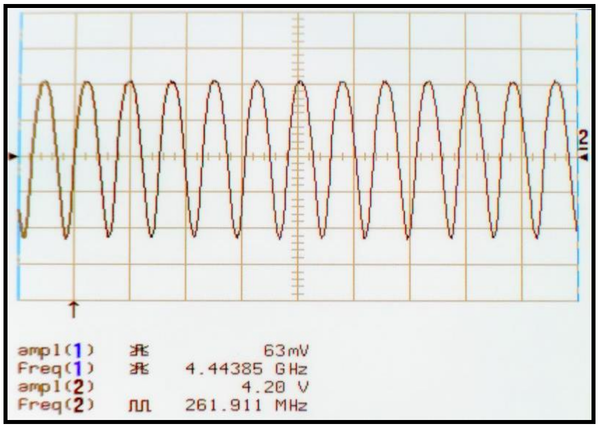

Fig.7. Photograph of the baseline frequency (261.9 MHz with amplitude of 4.2 V) of a Colpitts SAW oscillator sensor system shown at the channel 2 of an RF Oscilloscope.

The typical frequency shifts of a dual SAWR sensor after the detection of a volatile chemical compound (here an insect sex pheromone) shows that the one-port SAW oscillator provides a highly-sensitive system for chemical detection. The response has a low level of noise as shown in Fig. 8. On the introduction of 10 µl of the insect pheromone Z9-14:OAc into the odor chamber, a differential frequency shift of about 6 kHz was measured at the SAW output, which shows that the average sensor response to the pheromone compound is about 0.6 *Hz/nl* of liquid, i.e., sub-ppm levels of phermone in air.

The response time of the system is relatively slow (~100 s) and it is associated with the evaporation and diffusion of the volatile compound inside the chamber. However, the actual response time of the SAWR itself is below one second.

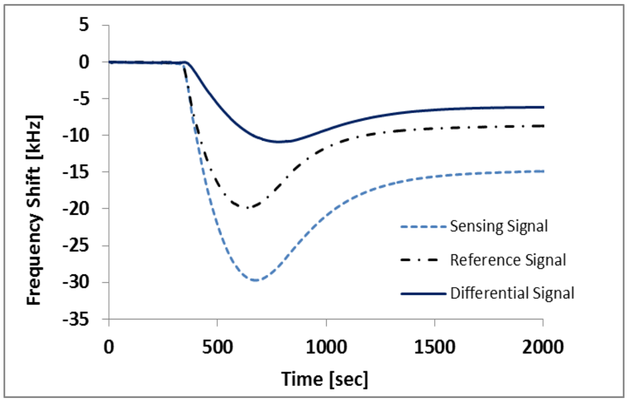

Fig.8. *Differential frequency response of polymer-coated SAWR sensor to pheromone Z9-14:OAc demonstrating the high sensitivity of the polymer-coated SAWR sensor.*

VI. CONCLUSION

A high frequency one-port Colpitts SAWR oscillator has been designed and fabricated for application in a low-cost, low-power gas sensor. An equivalent model has been developed, which formed the basis of an oscillator circuit design for a highly sensitive chemical sensor. The SAWR exhibits a high quality factor of 2,870 and has an estimated 0.5 Hz/ng mass sensitivity after coating with a thin gas sensitive non-conducting polymer film.

Further studies are being carried out on the detection of specific blends (i.e. mixtures) of chemical compounds. In addition, technological developments of this work include the creation of a smart low-cost, low-power chemical sensor on a chip - by the integration of the SAWR sensor with full custom CMOS oscillator circuitry thus resulting in an application-specific integrated circuit (ASIC) BioMEMS chip.

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