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Oscillator-based volatile detection system using doubly-clamped micromechanical resonators

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Abstract

In this paper, we demonstrate a functionalized and resonant piezo-actuated volatile sensor which is interfaced by electronics for frequency shift detection. Enhanced signal sensing is achieved via the effective feed-through capacitance cancellation scheme. The closed-loop oscillator, realized with off-the-shelf components, attains a frequency stability of 2.7 Hz for the 1.8 MHz resonant mode of the gas sensor. The sensor was exposed to pulses of water and ethanol vapor mixtures, yielding a temporary dip in resonance frequency as well as volatile-specific recovery times.

Keywords: functionalized sensor, gas detection, frequency shift detection, closed-loop oscillator.

1. Introduction

A wide range of applications, including healthcare and safety, require detection and identification of volatiles where a certain level of autonomy and miniaturization is desired. Resonant sensors are considered suitable for the task owing to their high sensitivity, scalability and arrayability. Among the remaining challenges for resonant sensors is an integrated readout scheme.

Previously, cantilever sensors interfaced by an on-chip Wheatstone bridge were demonstrated [1]. In [2], the sensor is a capacitive micro machined ultrasonic transducer combined to an amplifier and a band pass filter. In [3], a micro-bridge sensor is connected to an optical readout for the measurements of liquid properties. Yet, little work has been done on the electrical interface of piezo-actuated micro-bridge sensors.

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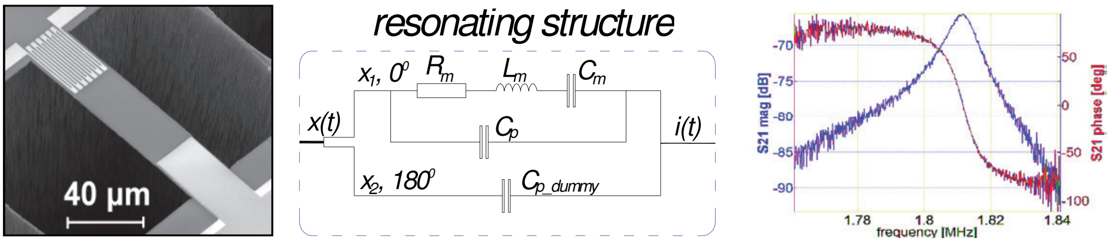
This paper reports on the design and characterization of a trans-impedance based oscillator readout made from off-the-shelf components. Our sensing mechanism relies on polymer-coated, doubly clamped micro-electromechanical beams with integrated piezoelectric transducers [4]. To our knowledge, we demonstrate for the first time a piezo-actuated, doubly clamped sensor interfaced by an oscillator-based readout for volatile sensing applications.

2. Piezoelectric MEMS resonator background



(a) (b) (c)

Fig. 1 (a) Lumped-model representation of the sensor with compensating element (C_{p_dummy}). (b) SEM picture of the resonant beam. (c) Measured magnitude and phase of the sensor electrical transmission, with parasitic compensation, around 1.81 MHz.

The resonant sensor is composed of a doubly-clamped beam, fabricated from silicon nitride by a thin film process (Fig. 1(a)). A piezoelectric transducer patch partially covers the top surface to bring the beam into resonance and to sense vibrations. Sensing is achieved by a polymer layer, which is coated from the backside of the sensor and which can absorb specific gas compounds from the environment, thereby modifying the resonance frequency. In Fig. 1(b), the lumped-element representation of the sensor is shown. It includes a $R_mL_mC_m$ resonant branch with a feed-through capacitance C_p. and a dummy compensation capacitance C_{p_dummy}. As proposed in [5], the dummy capacitance is processed on the same die as the resonator and is driven 180˚ out of phase. The enhanced sensor electrical characterization is shown in Fig. 1(c).

3. Oscillator-based readout implementation

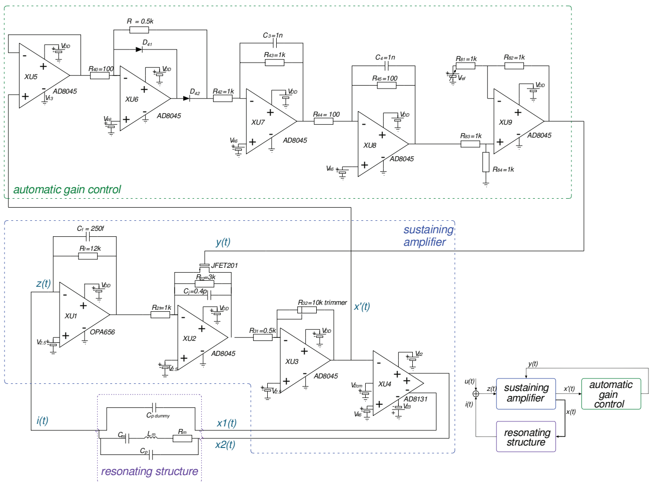
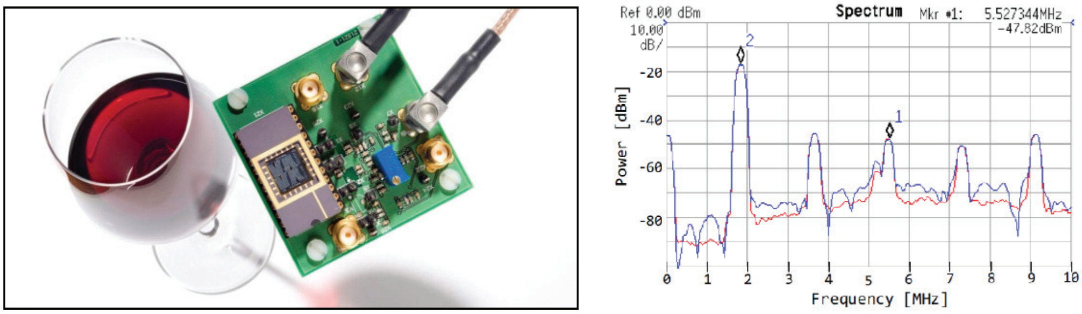


Fig. 2. Circuit implementation of the oscillator readout with the resonating structure representation. Bottom-right: High-level representation of the resonating structure, sustaining amplifier and automatic gain control.

The resonating structure is connected in closed-loop to a sustaining amplifier based on a four-stage trans-impedance amplifier (Fig. 2). A differential output ($x_1(t)$ and $x_2(t)$) is generated to drive the resonator and the compensation capacitance. The loop gain is tuned via a trimmer resistor, together with the automatic gain control, to ensure a stable loop gain and constant resonance signal amplitude.

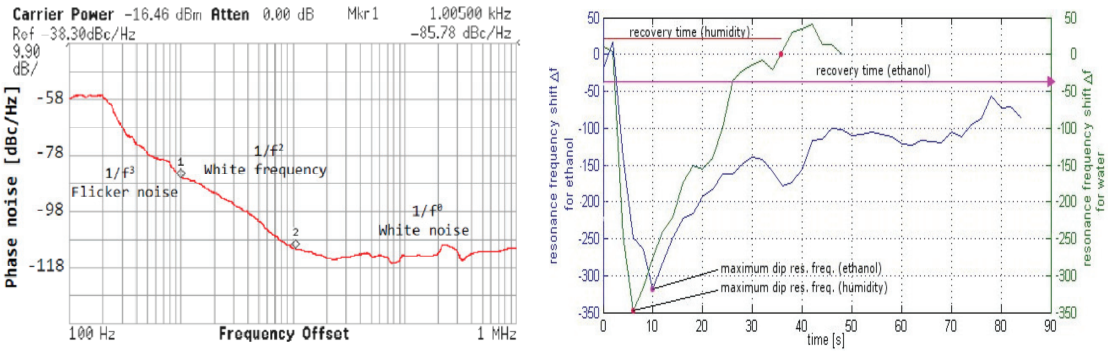
4. System characterization



(a) (b)

Fig. 3 (a) Illustration of the sensor and readout PCB used for ethanol and humidity detection tests (b) Measured Fourier spectrum of the oscillator from DC to 10 MHz, in air.

The implementation was successfully tested on a printed circuit board (PCB), with off-the-shelf components (see below, Fig. 3(a)). The oscillator Fourier spectrum is shown in Fig. 3(b). The resonant mode around 1.8 MHz is most dominant. Fig. 4(a) shows the measured oscillator phase noise which is -86 dBc/Hz at 1 kHz offset. This corresponds to a minimum frequency stability, also called Allan deviation, of 2.7 Hz as presented in [6].



(a) (b)

Fig. 4 (a) Measured oscillator phase noise versus frequency offset from the carrier frequency located at 1.81 MHz, in air.(b) Closed-loop sensor response to water and ethanol vapour. The dip in resonance is more than 300 Hz and the recovery time is shorter for humidity compared to ethanol.

As a proof-of-principle, ethanol and humidity vapours were applied to the closed-loop sensor (Fig. 4(a)). As indicated in Fig. 4(b), the oscillation frequency temporarily drops by more than 300 Hz due to the presence of ethanol and water. The recovery time is specific to the type of compound (35 s for water vapour, more than 90 s for ethanol and water). Table 1 summarizes typical key characteristics of the oscillator-based volatile sensor.

Table 1. Main oscillator characteristics, with typical ranges between brackets.

Variable	Value	Typical range
MEMS oscillation freq. [MHz]	1.8	(1-5)
Q	217	(100-300)
C_p [pF]	4.94	(1-5)
R_m [kΩ]	135	(50-200)
L_m [H]	2.58	(1-10)
C_m [fF]	2.99	(1-10)
C_p vs. C_{p_dummy} mismatch [%]	2	(0-5)
Actuation power [dBm]	-17	-
Allan deviation [Hz]	2.7	-

5. Conclusions

In this paper, we present an oscillator-based volatile detection system. This system features piezoelectric actuation of a doubly clamped MEMS resonator. The sensor is connected in closed-loop to a sustaining amplifier, which is made from off-the-shelf components. The Allan deviation in air is 2.7 Hz, at an oscillation frequency of 1.8 MHz. The corresponding phase noise at 1 kHz offset frequency is -86 dBc/Hz.

Exposure of the oscillator gas sensor to ethanol and water vapour mixtures yields a temporary negative frequency shift as well as volatile-specific recovery times. A system including a number of sensing elements coated differently is under development, to address the selectivity of different gas mixtures.

Acknowledgments

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