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High precision measurement of quality factor for MEMS resonators

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Abstract

In this paper, a novel CMOS circuit is proposed for MEMS resonator quality factor measurement. A reconfigurable circuit, in which a single OTA is used, is designed to implement both the required peak detection and comparison successively. After peak detection, the OTA's offset, which is considered as the major error source, is memorized and automatically cancelled during the following comparison, improving greatly the measurement precision. SPICE simulation of the proposed circuit shows a residual offset inferior to 200μV. The simulation based on a functional model gives a relative error lower than 1%, which is 4 times lower than that with offset.

Keywords: MEMS resonator; quality factor; CMOS; reconfigurable circuit; peak detection; comparison

1. Introduction

Vacuum packaged MEMS resonators feature high quality factor (Q > 10000). They can be used in high precision sensors systems. To ensure accurate measurements, a precise knowledge of the effective quality factor is of great importance. From the literature, two measurement principles can be found: frequency-domain measurement and time-domain measurement. Frequency-domain measurement is the most exploited technique until now [1]. However, such a measurement, requiring spectral analysis, is generally performed off chip. Time-domain measurement offers the possibility of a simple on-chip implementation. This allows detecting components that become faulty because of aging phenomena or leakage in the packaging.

In this paper, an integrated time-domain quality factor measurement architecture is proposed. The measurement principle and the performance analysis are presented in section 2. The newly proposed offset-free circuit is presented in section 3, followed by the simulation results in section 4. Some summaries and conclusions are given in section 5.

2. Time-domain measurement principle and performance

We suppose that the to-be characterized MEMS device is used within an integrated oscillator working at its resonant frequency. In test mode, the loop is opened and the subsequent damped oscillations are monitored. The equation of this transient response is given below:

$$\mathbf{V(t) = V_0 e^{-(\frac{\omega_0}{2Q})t}\left[\cos\left(\omega_0 t\sqrt{1-\frac{1}{4Q^2}}\right)+\frac{1}{\sqrt{4Q^2-1}}\sin\left(\omega_0 t\sqrt{1-\frac{1}{4Q^2}}\right)\right]} \tag{1}$$

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Determining Q consists in counting the pseudo periods between two predefined reference voltages, as illustrated in Fig. 1 a). The quality factor can then be deduced by Eq. (2):

$$Q = \sqrt{1 + \left(\frac{n \cdot \pi}{\ln(k)}\right)^2} \approx \frac{n \cdot \pi}{\ln(k)} \quad (2)$$

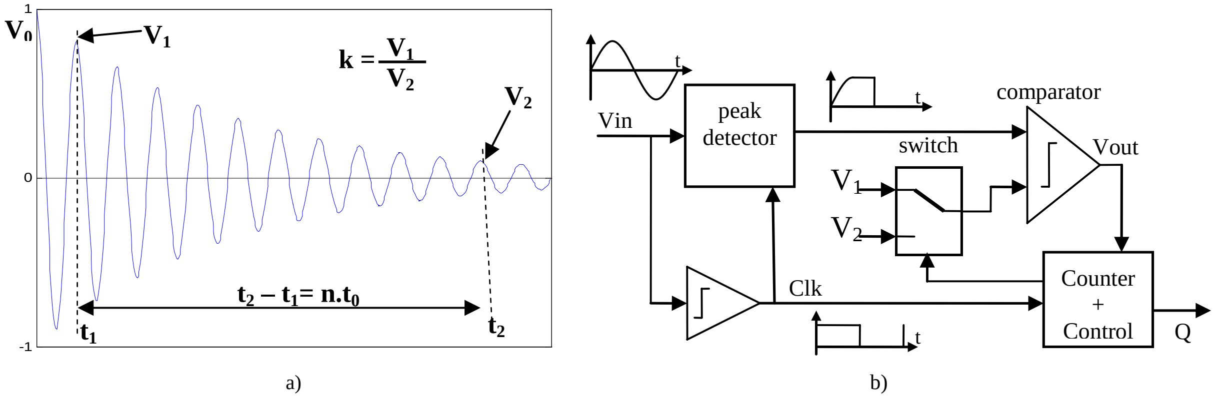

Fig. 1. Proposed time-domain quality factor measurement principle a) and architecture b).

Fig. 1 b) shows a first mixed signal architecture to perform this measurement [2]. A peak detector is used to sense each damped peak voltage which is then compared to the predefined reference voltages. A second comparator is used to generate a clock signal from the damped input voltage for the digital part. This clock signal is also used as resetting signal for the peak detector.

The static non-idealities (e.g. OTA's offset or reference voltages' error) have been introduced in a functional model to evaluate the measurement performance of this architecture. As shown in Fig. 2, worst case non-idealities values lead to a minimum error of 4%. This limit is mainly due to the circuits' offset.

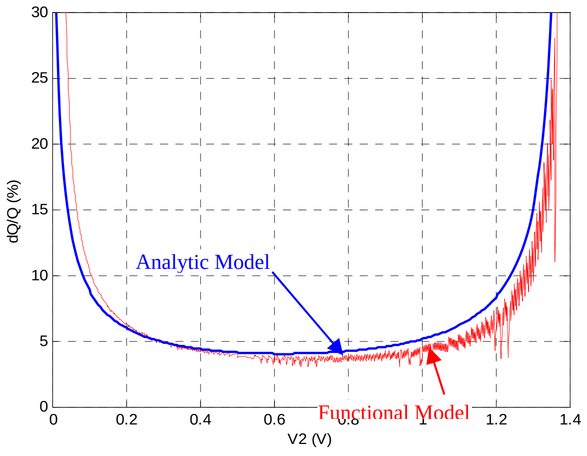

Fig. 2. Simulation of the relative error (offsets 10mV, reference voltage error 5mV, Q=1000)

3. Proposed circuit

In order to improve the quality factor measurement precision, an original analog circuit is proposed in this paper. Instead of implementing both peak detection and comparison separately, a unique configurable circuit is proposed, in which a single OTA is used to perform both peak detection and comparison successively. In the presence of OTA's offset, the same offset will be found for peak detection as well as comparison. By adequately designing the two configurations offered by the configurable circuit, the offset's influence on the measurement of pseudo periods can be cancelled automatically.

The proposed circuit is illustrated in Fig. 3 a). When the circuit works as a peak detector, the corresponding configuration is shown in Fig. 3 b) [4]. As long as no peak voltage is detected, the holding capacitor is kept charging by the current mirror so as to follow the input voltage with only the difference of the OTA's offset between the two voltages, that is, $Vc = Vin - Voff$. Whenever a peak voltage occurs, the OTA's output is switched up, which stops the capacitor's charging. As a result, the peak voltage together with the offset is stored onto the holding capacitor.

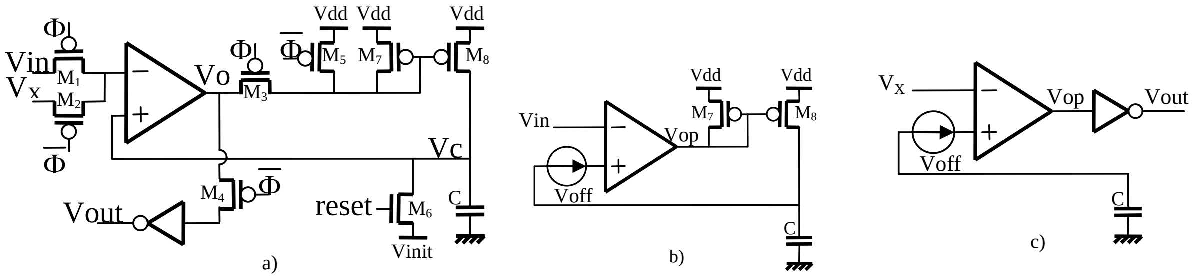

Fig. 3. a) Offset-free peak detection and comparison circuit; b) peak detector configuration; c) comparator configuration.

Then the sensed peak voltage is compared to the reference voltage with the comparator's configuration. As shown in Fig. 3 c), the voltage which will be compared to Vref is the OTA's positive input voltage, that is, $V^+ = Vc + Voff = Vin$. As a result, the OTA's offset is cancelled, resulting in offset-free quality factor measurement.

4. Simulation results

The proposed circuit is simulated in a CMOS 0.35µ technology. To verify the operation of the proposed offset cancellation, an offset of 3mV is artificially added to the OTA used. SPICE simulation (Fig. 4) clearly shows the difference between the input signal's peak and the sensed peak signal.

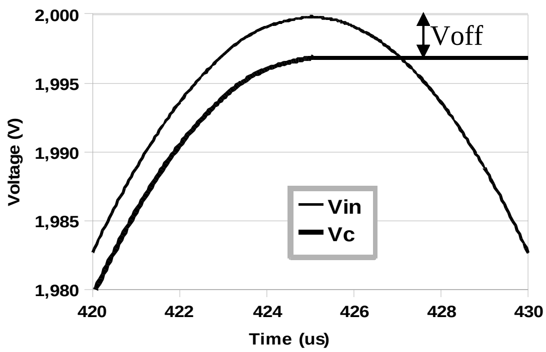

Fig. 4 Zoomed SPICE simulation of peak detection

The whole operation of the proposed circuit is simulated and the simulation results confirm the proposed offset cancelling principle (Fig. 5). According to the simulation results, a residual offset inferior to 200µV is obtained. Based on the functional model we developed and taking into account only OTA's offset of 200µV, a relative error of quality factor measurement is found lower than 0.2% (Fig. 2). If all the static non-idealities parameters are taken into account, the relative error can still be lower than 1%.

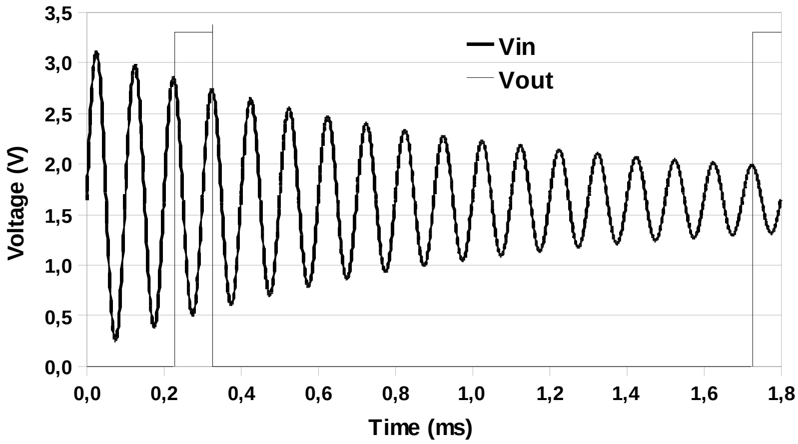

Fig. 6 SPICE simulation of the proposed architecture

5. Conclusion

A CMOS integrated circuit for MEMS resonator quality factor measurement is proposed. Based on a time-domain measurement principle, this circuit has a compact architecture only featuring a counter, a peak detector and two comparators. A naïve straightforward implementation has a performance limited by the offsets of the peak detector and the comparator. To increase this performance, an original reconfigurable topology is proposed to perform both functions sequentially. An offset- free quality factor measurement is thus obtained. The measurement error is then 20 times smaller if only the offsets are taken into account.

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