MEMS Based AC Voltage References: towards Metrological Applications

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ABSTRACT

This paper presents the high-level of stability of voltage references operated in alternating current (AC) and based on the pull-in effect in split-fingers. Secondary references are the key points for precision measurement or electrical conversion. In this paper we bring a clear enhancement of performance. Indeed, the voltage stability of MEMS devices designed to serve as AC voltage standards ranging from 2 V to 14 V has been measured over more than 150 hours with a relative deviation from the mean value not exceeding 1×10^{-6} (1σ standard deviation) at 100 kHz. Moreover, their temperature dependence is ten times smaller than previously reported. In addition, MEMS-based structures are theoretically independent of the frequency of use when working beyond the resonant frequency. This frequency stability has been successfully tested between 40 kHz and 350 kHz.

Keywords: MEMS, Electrical Metrology, AC voltage, Pull-in effect.

1 INTRODUCTION

In metrology, primary references designate the standards, which serve to define and maintain the fundamental units of the International system of units (SI). These standards are known with the lowest uncertainties and exhibit the highest stability as possible. The secondary references designate a system generally with lower precision, which is periodically compared to the primary standards to be calibrated. The stability as well as transportation are the key points for these references.

In electrical metrology, since 1990, the Consultative Committee of Electricity and Magnetism (CCEM) recommended to maintain the volt unit through the alternating Josephson effect by implemented a superconducting mono junction or a array of thousands of junctions by fixing the Josephson constant at the exact value of $K_{J\text{-}90}$ = 483597.9 GHz/V [1,2]. At this primary metrology level, the array Josephson standards present the best uncertainties ($<10^{-9}$) with a range of voltage values limited by the number of possible junctions in the array (the typical values of these standards are 1 V and 10 V). Until now, only National Metrology Institutes (NMIs) use these references for the conservation of the volt because of the high cost of the experimental set-up and the use of cryogenics. At lower level, the best secondary references of DC voltage are Zener diodes (1 V and 10 V) equipped with an integrated electronics for temperature compensation [3].

Currently, the only references of AC voltage are generated by arrays of Josephson junctions used as a programmable analog-to-digital converter. The development of these components is still far from being completed and they suffer from the same limitations as in the case of the DC Josephson: in terms of accessible values (max 10 V), practical implementation and a frequency band limited by the sampling techniques. In addition, the best uncertainties in linking AC voltage with AC-DC thermal conversion remain limited in frequency band up to 100 kHz (uncertainty of 10^{-7} at 1 kHz and of 10^{-6} up to 100 kHz) [4].

The development of MEMS AC voltage references working beyond 100 kHz will undoubtedly constitute an outstanding progress.

2 PRINCIPLE OF OPERATION

In this application, the basic concept is the electromechanical transduction in MEMS in which the high mechanical stability of a single crystal of silicon would be transferred to an electrical stability through the mechanical-electrical coupling. Such devices are made of two micro-machined electrodes in which one at least is movable thanks to the application of an electrostatic force between the two electrodes separated by a gap d.

When the structure is driven by a DC voltage V_{in}, the output voltage $Vout$ presents a maximum as illustrated by figure 1. The maximum of the output voltage is called the pull-in voltage V_{pi} due to the semi stability of this point. For $V<Vpi$, each point of the curve could be physically reached but for $V>Vpi$, the movable part goes to stick to the fixed one irremediably. The value of Vpi is given by the following equation.

$V_{pi}= (8kd^2 / 27 C_0)^{1/2}$ (1)

where C_0 is the capacitance at rest and k the spring stiffness.

However, when the structure is biased by an AC sinusoidal current of amplitude I_{RMS} and a frequency ω above the fundamental mechanical resonance, the AC output voltage presents, according to the current I_{RMS}, a maximum (Fig. 1) equal to the pull-in voltage V_{pi} given by equation (1). But in this case, all points of the curve are stable and could be reached.

By convenience, this maximum is also called pull-in voltage. Actually, it is simpler to get stabilization at this maximum and takes benefits of the value of the slope equal to zero. So, this maximum voltage can be used as a stable AC voltage reference since its relative variation in this point depends only on the square of the relative variation of the current:

$$\Delta V_{RMS}/V_{pi}= -3/2\ (\Delta I/I_{RMS\text{-}max})^2 \quad (2)$$

From a mathematical point of view, we can notice that the equation (2) is verified for all the frequency above the fundamental mechanical frequency. This implies that, theoretically, there is no limitation to increase the operating frequency and realize AC reference up to the MHz region or more with the same characteristics. This is a truly advantage compare to the classical AC-DC thermal conversion of which the precision decreases when the operating frequency increases. In addition, MEMS structures have in general a mechanical resonant frequency of some kHz. So the working frequencies will be above 10 kHz in order to be enough far away from this resonant frequency. So the MEMS reference could be compared with AC-DC thermal conversion at lower frequency (30 kHz) and then used in a higher frequency region.

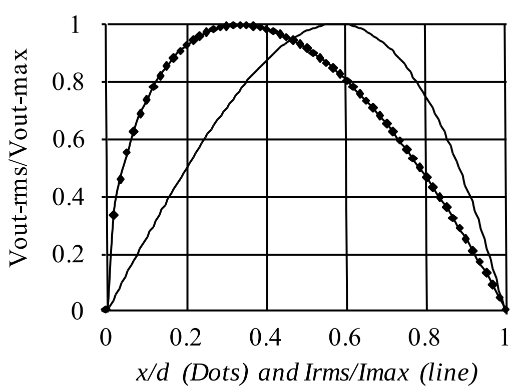


Figure 1: MEMS voltage (or output voltage) normalized to the maximum output voltage versus the normalized position in the gap for line with dots and versus input AC current normalized to its maximum for line without dots (both are experimental data).

3 SYSTEM DESCRIPTION

3.1 Mechanical part

A voltage reference consists of a MEMS associated with its read-out electronics. In our case, the electromechanical element is a MEMS variable capacitance achieved through a technological process available at Tronic's Microsystems as part of a MPW service [http://www.tronicsgroup.com]. Figure 2 illustrates a MEMS used for our study. The MEMS is realized from a silicon-on-insulator wafer (SOI) to take benefits of excellent mechanical properties of the single-crystal silicon, which is a key point for this application.

The single-crystal silicon is well known to have less fatigue than polysilicon as the mechanical stress is low. Structures in single silicon crystal are able to tolerate up to 10^{10} cycles without any crack or fatigue. However, minimizing the stress suffered by the mechanical elements is a basic rule in the absence of precise knowledge of fatigue under constant load below 1 GPa [5-8]. Finally, the MEMS is bounded by an eutectic on a classical TO8 support using Au-Sn sheet. The measured capacitance is equal to 8.3 pF at the rest with a built-in voltage of 0.8 mV. The maximum voltage measured at the pull-in point is 9.4 V for samples targeted for 10 pull-in voltage.

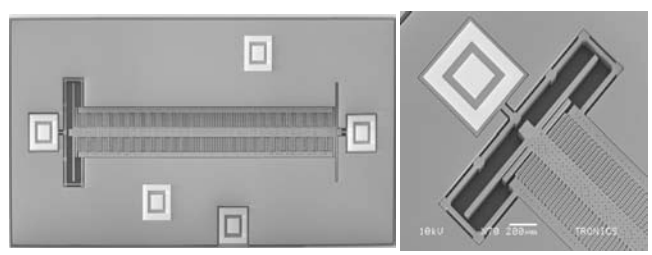


Figure 2: View of the MEMS: a global view and a zoom around the left side of the structure.

3.2 Electrical part

To drive the MEMS to the pull-in voltage for defining the AC voltage reference, we have developed read-out electronics able to adjust automatically the output voltage of the MEMS to its maximum value. Figure 3 illustrates the experimental set-up which integrates a temperature regulation of the MEMS by using small Peltier modules ensuring temperature stability at some mK. To drive automatically the MEMS to the pull-in position, a proposed solution consists in controlling the operating point using an amplitude modulation (AM) of the RF signal, typically at 100 kHz, by a small sinusoidal signal at very low frequency. Indeed, such a feedback-loop eliminates many error sources, and the only remaining error is the amplifier gain.

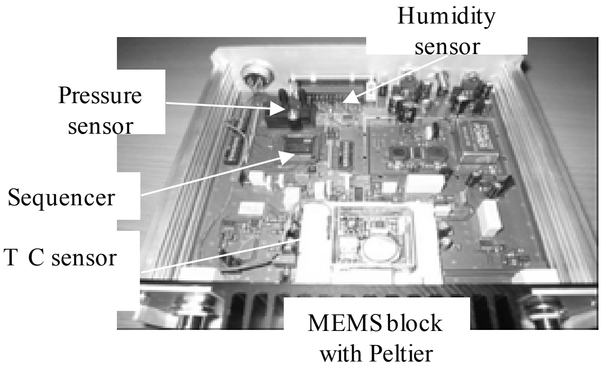
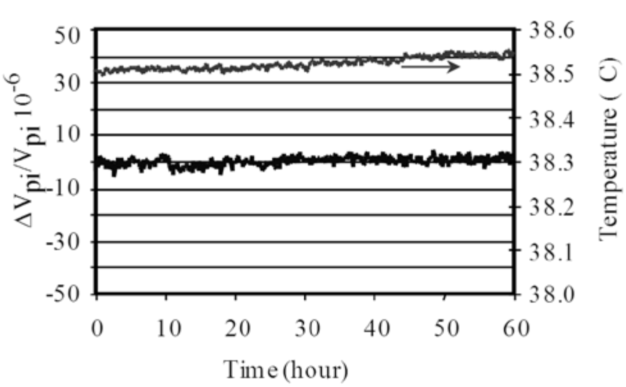


Figure 3: General view of the complete system: MEMS + read-out electronic.

4 EXPERIMENTAL RESULTS

4.1 Stability over time

The stability measurements of the AC voltage reference, corresponding to the maximum of the *V-I* curves, have been performed on several MEMS devices of the same design (Fig. 4). The driving current is supplied by a precision calibrator (Fluke 5720A). The MEMS RMS output voltage is measured by a digital voltmeter (Agilent 3458A) put in the AC analogue mode with an integration time of 10 s. Moreover, the read-out electronics is fitted with temperature, relative humidity and pressure sensors. These environment parameters have been kept as stable as possible and are measured simultaneously with the MEMS output voltage. The mean standard deviation (1σ) of the pull-in voltage measurements for this device is about 1 ppm over 150 hours, which is at 100 kHz, an excellent result. Let us notice that the measured stability of our MEMS structures include the stability of the MEMS output voltage, which depends on the electronics performance and its noise level, and also the stability of the digital voltmeter put in the AC analogue mode and measuring at 100 kHz.



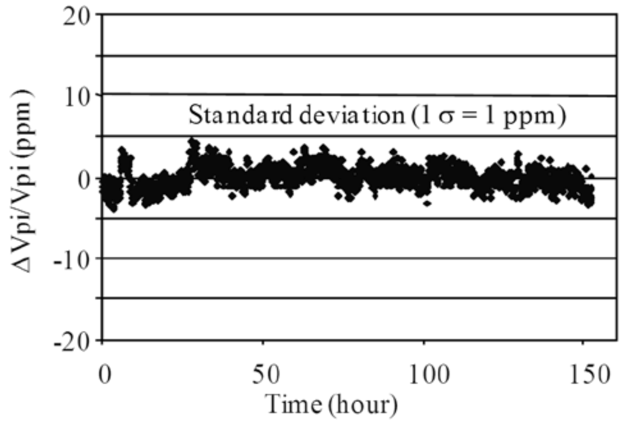


Figure 4: Two examples of stability obtained with two MEMS of the same type. At the top, evolution with a slow temperature drifts. Below, a more long time evolution with a temperature control activated.

4.2 Temperature dependence

We have operated measurements on MEMS structures with the aim to characterize their behavior according to environmental parameters. To determine the temperature coefficient changes in the output voltage of the MEMS are measured following thermal stimuli controlled. Figure 5 shows an example of these measurements where the MEMS device is subjected to cyclic variation of temperature from 32 ° C to 34 ° C. The pull-in voltage varies in this case by an average of 70 ppm in relative for a temperature variation of 2 ° C. The temperature coefficient of the MEMS is thus of 35 ppm / ° C. These temperature coefficients were determined on several samples and vary between 32 ppm/°C and 40 ppm/°C [9]. These coefficients are 10 times lower than those found in other publications [10].

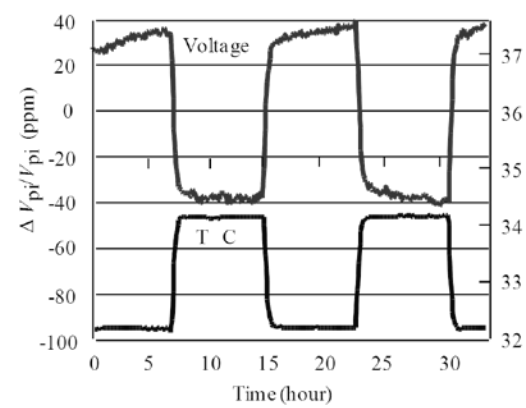


Figure 5: Measurements of the MEMS output voltage when the temperature varies between 32 ° C and 34 ° C.

4.3 Frequency dependence

We have characterized the MEMS voltage references according to the alternating current frequency between 5 kHz and 300 kHz. Figure 6 shows the typical relative variation of the pull-in voltages of MEMS as observed in the first experiment. The behavior is the same for all structures with a first peak at very low frequency corresponding to the mechanical resonant frequency of the system, and then a series of peaks occurring around 50 kHz, 100 kHz, 150 kHz, 200 kHz, 250 kHz and 300 kHz. Then, we have characterized the set-up without the MEMS voltage reference and its read-out electronics. The same frequency peaks have been found characterizing the multimeter behavior itself. For the frequency behavior of the voltage references, it is sufficient to correct the previous data by the variation due to the multimeter. Figure 7 shows the result obtained after subtraction of the variations due to the multimeter. We can show that the pull-in voltage of the MEMS structure is relatively constant over a wide range of the alternating signal frequency, beyond the mechanical resonant frequency of the system. With this sample, the voltage curve as a function of the frequency has a peak at 139 kHz corresponding to a vibration mode of the proof mass that is not present in all of our structures. Indeed, this resonance is related to the fact that the seismic mass of this sample is larger and therefore more flexible.

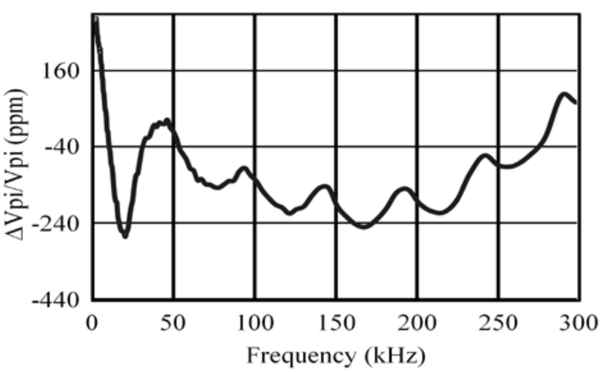
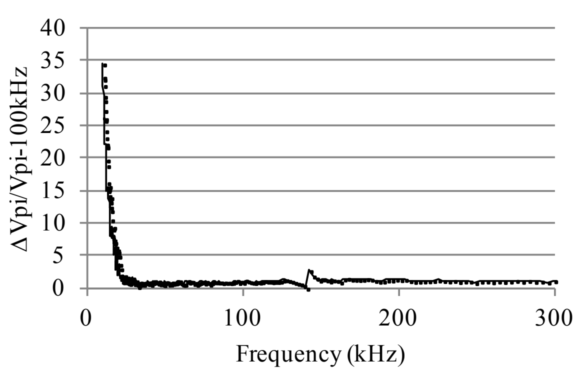


Figure 6: First measurement of the output voltage of the MEMS between 5 kHz and 300 kHz.



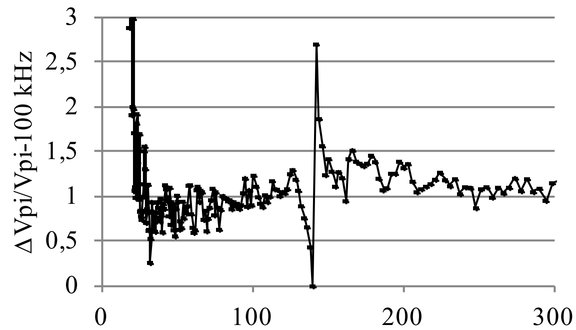


Figure 7: Relative variation of Vpi versus the AC current frequency: large scale (top) and zoom

5 CONCLUSION

This study presents an increase in performance of MEMS based AC voltage reference. Using commercial available components, specifically designed for this application, we have demonstrated the possibility to obtain stability in the range of 1 ppm of standard deviation over 150 hours. The thermal coefficient has been measured with an average value of 36 ppm/°C. This value is ten times better than those values founded in literature and allows getting a stability of 1 ppm by controlling the temperature in tenth of degrees. In addition, we have experimented the system behavior versus the frequency of use between 5 khz and 300 kHz. The preliminary results show that we can expect a flat response versus frequency in this range if we perform specific design to avoid resonant mode of the seismic mass.

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