Active Frequency Stabilization Method for Sensitive Applications Operating in Variable Temperature Environments

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Abstract—**This article proposes a cost efficient and easy to implement frequency stabilization method orientated toward communication systems operating in an extensive temperature range, as the automotive or the aerospace applications. The proposed solution uses off-the-shelf components and it is optimized for very low power consumption. The novelty of this article is represented by the introduction of the barium strontium titanate capacitor for quartz crystal oscillator active frequency stabilization. After the design was completed, the performances were evaluated and compared to the ones of the uncompensated oscillator. Experimental results confirmed the suitability of the proposed design, achieving 35 times better frequency stability within variable temperature conditions, whereas the power consumption is maintained below 6mW.**

Index Terms—**automotive electronics, automatic frequency control, barium compounds, thermal stability, voltage‐controlled oscillators.**

I. INTRODUCTION

In the last decades, the complexity of spatial systems and the amount of transferable data have increased. The simplest solution toward this goal is to increase the frequency of the data carrier and thus, larger spectrum bands can become available. Nevertheless, as the frequency is increasing, the requirements for the stability of the internal oscillator become more stringent. Initially, most of the applications were quite flexible regarding the synchronization needs (e.g. the second generation of mobile telephony). However, as the technology is evolving the frequency accuracy is becoming essential for an increasingly number of applications [1], [2].

The precision and/or the stability of an oscillator are evaluated through the $\Delta f/f$ report expressed numerically or in parts per million (ppm). It is well-known that due to various factors (i.e. temperature variation, voltage, or system aging), as the oscillator frequency (f) is increasing, the absolute frequency variation (Δf) increases as well. Thus, the frequency band reserved to a certain channel can end up overlapping the one of an adjacent channel. Of all the perturbing factors, the temperature variation has the strongest impact on the oscillator's stability. Consequently, the research community and the industry aimed to find various solutions to achieve frequency stabilization within temperature variation conditions. Initially, the stabilization was mechanically achieved with the help of a bimetal element which was modifying the inductance or the capacity of the oscillator. Another classical approach is based on ceramic capacitors having positive and/or negative capacity coefficients, which are modifying the frequency according to the temperature variations. Quartz crystals are also in use to achieve frequency stabilization, having remarkable results. In their case, the frequency variation curve is given by the quartz-cutting angle, as illustrated in Fig. 1 [3].

Nowadays, the Oven Controlled Crystal Oscillator (OCXO) is a widely used method to achieve a stable frequency [4-6]. In this case, the oscillator is heated and maintained at a temperature few degrees higher than the highest expected temperature, and thus, temperature deviations are prevented. Although this method is very efficient in terms of frequency stabilization, it has as a major drawback the high energy consumption. Another commonly used stabilization technique is based on a microcomputer compensated crystal oscillator (MCXO) [3], [6]. The method was increasingly applied in many applications, as in the case of mobile phones (i.e. compensation using varicap diodes) or in Microelectromechanical Systems (MEMS) oscillators [7-9]. Compared to the uncompensated oscillators, this solution enhances the stability by several orders of magnitude. On the downside, this solution is quite complex, and in some cases the energy consumption is rather high. It should be mentioned, that besides the general purpose applications, there are also applications in which the accuracy is highly essential (e.g. GPS satellites, laboratory and military equipment) and thus, the budget is less restrictive. In these cases, high performance rubidium or cesium based atomic clocks are used due to their enhanced performances [10-12].

Even though the upper mentioned solutions proved their efficiency in terms of frequency stabilization, the high power consumption, the high weight/volume or the high price can be considered major drawbacks in some applications. Thus, when restrictions apply, choosing the optimal solutions is rather difficult. For example,

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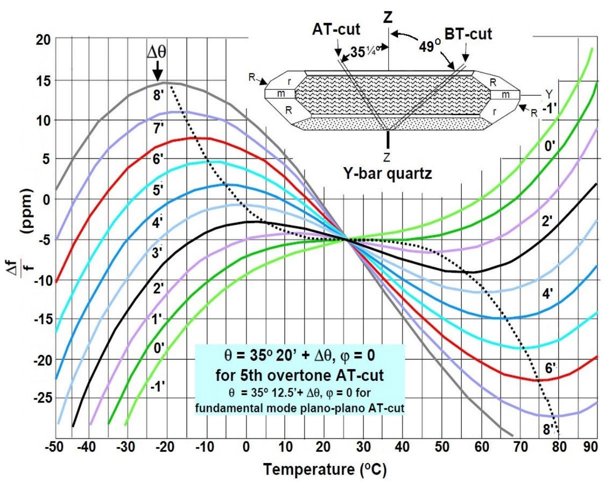

Figure 1. Curves of frequency variation with temperature, as a function of the quartz crystals cutting angle [3]

communication-based vehicle applications [13] require high performance communications, whereas the automotive industry is always struggling to reduce the cost of the components. Another example is the CubeSat satellite series [14] which is limited to a 1 dm^3 volume, 1 kg weight, and a total available average power below 1W (for the 1U format). Within such contexts, using one of the upper mentioned solutions is totally unfeasible.

On the other hand, although early research has showed that the Barium Strontium Titanate (BST) dielectric has the property to modify its dielectric constant by applying different electric field levels, recent research have shown that this property could be used to develop voltage-controlled capacitors, which in turn, can be used to improve the performances of the oscillators [15-17]. Thus, the newly developed oscillators showed better linearity, enhanced phase noise performances, lower harmonics, and better thermal stability. In [18], the BST capacitor is used in a voltage controlled LC oscillator in order to ensure lower phase noise and enhanced thermal stability. In [19] and [20], the performances of the BST capacitor are compared to the ones of the varicap diode. These results showed that the BST capacitor has better linearity of the variation frequency with respect to control voltage and also better signal spectral purity.

Within the upper-mentioned context, this article addresses the problem of frequency stabilization under the influence of strong temperature variations. Solving the problem of frequency variation has the potential to significantly enhance the stability, with effect on the Bit Error Ratio (BER) and on the throughput. Thus, temperature variations between -20 and +85° C and power supply restrictions are considered (i.e. maximum of 8 mA at 3.5 V) [21]. Unlike the exiting solutions, which use the BST capacitor in LC oscillators, this article addresses the usage of a BST capacitor in a quartz crystal oscillator, along with a low power crystal driver, enabling the usage in applications requiring an enhanced frequency stability under variating temperature conditions. As far as we know, this is the first article addressing this issue using this approach. Thus, the main contributions of this article are the usage of the BST capacitors in digital temperature compensated crystal oscillator (DTCXO) along with a hardware design optimized for very low power consumption applications. Unlike in [15-19], where the BST capacitors were laboratory developed, and thus, their designs and results are rather difficult to recreate by others, in this case, off-the-shelf BST capacitors (commercially referred to as STPTIC) have been used. Therefore, our design can be easily reproduced or further enhanced by others, favoring the transition toward commercial applications. This design is envisioned to be used in outdoor frequency sensitive applications, as the wireless vehicular communications [22-24] or in low power satellite applications. The rest of the paper is organized as follows: Section 2 presents the concept of the active frequency stabilization, Section 3 presents the evaluation of the BST capacitor, Section 4 describes the hardware design and the experimental results, whereas Section 5 presents the conclusions of this work.

II. Design of the Active Frequency Stabilization Oscillator

Among the oscillators presented in Table I [3], the Microcomputer Compensated Crystal Oscillator (MCXO) seems to be the one that best fits with the frequency stability requirements, and also with the very low consumption demand. In this case, the oscillator frequency variations are actively compensated by a microcontroller. Thus, it is possible to compensate all frequency variations caused by the temperature influence, by voltage supply variations, and by components aging. Furthermore, in extreme situations, the MCXO can also compensate for variations due to mechanical influences (e.g. vibration, acceleration).

TABLE I. Summary Presenting the Characteristics of the Existing Oscillators [3]

Oscillator Type	Accuracy	Aging/ 10 year	Radiation Per RAD	Power	Weight [g]
Crystal oscillator (XO)	10^{-5} to 10^{-4}	10-20 PPM	-2 x 10^{-12}	20 μW	20
Temperature compensated crystal oscillator (TCXO)	10^{-6}	2-5 PPM	-2 x 10^{-12}	100 μW	50
Microcomputer compensated crystal oscillator (MCXO)	10^{-8} to 10^{-7}	1-3 PPM	-2 x 10^{-12}	200 μW	100
Oven controlled crystal oscillator (OCXO) - 5 to 10MHz - 15 to 100MHz	10^{-8} 5 x 10^{-7}	2 x 10^{-8} to 2 x 10^{-7} 2 x 10^{-6} to 11 x 10^{-9}	-2 x 10^{-12}	1 – 3 W	200-500
Small atomic frequency standard (Rb, RbXO)	10^{-9}	5 x 10^{-10} to 5 x 10^{-9}	2 x 10^{-13}	6 – 12 W	1500-2500
High Performance atomic standard (Cs)	10^{-12} to 10^{-11}	10^{-12} to 10^{-11}	2 x 10^{-14}	25 – 40 W	10000-20000

Considering the upper-mentioned, this article proposes a 16.384 MHz Voltage Controlled Crystal Oscillator (VCXO) crystal oscillator used as reference for time scheduling (16.384 MHz divided by 500 equals 32.768 Hz – the most commonly used frequency in clock and time applications) and as a frequency reference to one or more Phase Locked Loop (PLL) circuits responsible to generate the required frequencies. The active frequency stabilization oscillator block design is illustrated in Fig. 2. The design mainly englobes a VCXO, a 16-bit digital-to-analog (DAC) converter, and a microcontroller with built-in thermometer. Fig. 1 illustrates the frequency variations with respect to the temperature for a typical quartz crystal having an Anti-Thermal (AT) cut. However, these curves are relevant only for the crystal itself and not for the oscillator as a whole. Nevertheless, the oscillator has other temperature-sensitive components influencing its frequency (i.e. capacitors, active elements, etc.). To compensate these variations as well, the microcontroller uses a voltage correction table, determined for each individual oscillator. The voltage compensation table is determined by combining the frequency variation graphs with respect to the temperature variation and to the control voltage.

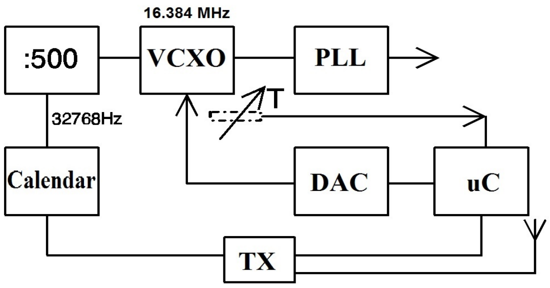

Figure 2. Block diagram for the generation of the active stabilized frequencies

In order to enhance the frequency stability and the precision, the reference has been positioned in the same compartment as the microcontroller, preventing thermal offset deviations. Thus, we obtained a MCXO or DTCXO. Unlike the existing solutions, which measure only the temperature of the quartz crystal, with the introduction of the loop compensation oscillator in the same compartment, the proposed solution will compensate all thermal influences, including the ones due to electronic components (capacitors, voltage references, etc.). In addition, the design can also compensate the frequency variation due to crystal aging.

III. The Experimental Verification of the BST Capacitor Performances

The design of the active frequency stabilization oscillator and the initial experimental verification started from the hypothesis according to which the performances of an oscillator can be significantly enhanced by replacing the varicap diode with a BST capacitor. To confirm this premise, we have decided to evaluate the performances of a commercial oscillator (TCO-9133) and to determine the enhancement that can be brought by the BST capacitor. This oscillator is supposed to have a +/- 2.5ppm frequency stability for temperature between -30 and 70^{0} C. The first measurements were conducted in order to determine the frequency stability, both for the original configuration with a 26 MHz crystal and also for a 16.384 MHz crystal, as the one required for our future application [23]. Fig. 3 shows the variation in frequencies for the two crystals, as a function of the control voltage. In both cases, the maximum frequency reached at a control voltage of 3.9V is considered as a reference. As illustrated in Fig. 3, the replacement of the crystal resulted in a decrease of the control frequency range (ΔF), from 2200 to 1600 Hz. Thus, the deviation of frequency variation linearity is between 48 and -130 Hz. In the next phase, the two oscillators (with a 26 MHz crystal and with a 16.384 MHz crystal) were introduced in a thermostatic enclosure (based on two Peltier elements controlled by a microcontroller) in order to determine their behavior in temperature variations between 10 and 77^{0} C. As showed in Fig. 4, this trial indicated that the replacement of the crystal created a higher frequency drift with temperature: 720 Hz for 16.384 MHz quartz oscillator, compared to only 204 Hz for the original 26 MHz oscillator.

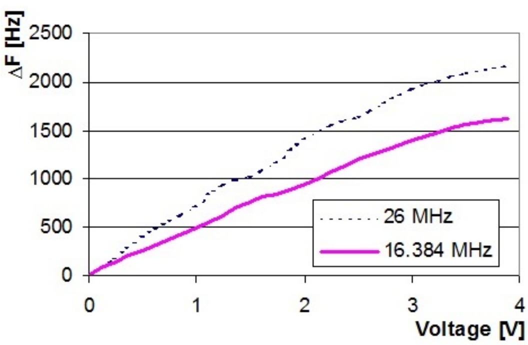

Figure 3. Frequency deviation depending on the driving voltage for the two crystals

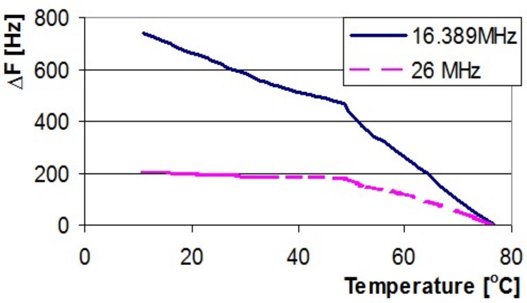

Figure 4. The graphs of the frequency variation versus temperature

The next set of measurements was performed after replacing the control frequency varicap diode, with a 6.8pF controllable BST capacitor, commercially referred to as STPTIC. Referring to their design, it should be mentioned that the BST capacitors have 3 terminals: RF1, RF2 and Bias (the DC control voltage), and they are mounted in a WLCSP package of 0.6 x 0.8 x 0.3 mm, using the micro BGA technology. The BST capacitor and the varicap diode have a rather similar capacity variation characteristic as a function of the applied control voltage. Nevertheless, a particular parameter of the BST capacitor is that unlike the varicap diode, their capacity is not influenced by the radio frequency voltage, and so, the signal distortions and the harmonics levels are significantly lower. Therefore, it can be considered that these BST capacitors (STPTIC) are well suited for emission tuning circuits having powers up to 33 dBm [24]. In the next step, we aimed to determine the oscillator frequency variation as a function of the applied voltage, when the BST capacitor is used. As shown in Fig. 5, this variation has a better linearity compared to the case when the varicap diode was in use (Fig. 3), enhancing the circuit predictability.

Further on, the entire assembly was placed in the thermostatic enclosure and it was tested in a temperature range between 10 and 77° C (with the control voltage equal to 1.25V). As illustrated in Fig. 6, the oscillator frequency has a very good stability, significantly better compared to the one of the original oscillator with varicap diode and a 26 MHz quartz crystal. One can observe that the maximum control range (Fig. 5) is significantly higher than the required one, ensuring the compensation of the frequency thermal instability (Fig. 6). In this case, the deviation of frequency variation linearity is between 64 and -42 Hz.

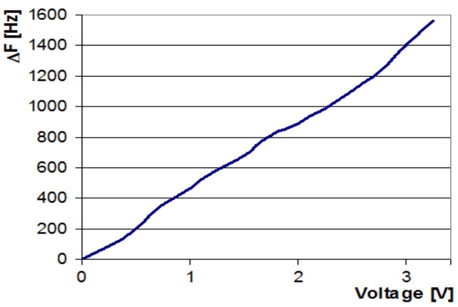

Figure 5. Frequency variation with respect to voltage, using a STPTIC capacitor

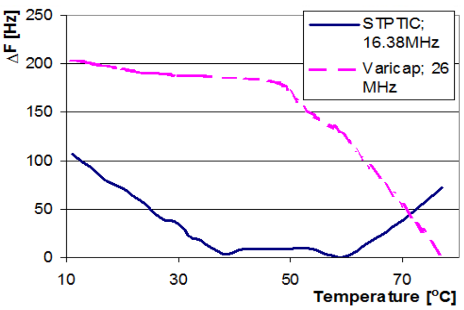

Figure 6. The thermal stability of the oscillator controlled by the BST capacitor

IV. Oscillator Design and Experimental Verification

A. Oscillator design

After demonstrating the enhanced performances of the BST capacitors in a commercially available oscillator, the next step was to move toward the development of a custom made oscillator having the proper characteristics for the envisioned applications (i.e. low power consumption, increased thermal stability and a 16.384 MHz quartz crystal). The schematic of the oscillator is illustrated in Fig. 7. It uses the 74AUP1Z125 integrated circuit as a low power crystal driver. This circuit is specially intended for very low consumption quartz oscillators, and thus, the power consumption decreases from 2mA to 75uA. The VCXO schematic also includes the BST capacitor, its control circuit, whereas the 1 μH coil is introduced in order to ensure an adequate adjustment range, centered on the 16.384 MHz frequency. After establishing the oscillator design, the next step was to determine the frequency variation with respect to the control voltage (Fig. 8). This graph illustrates the circuit control limits (16.382 – 16.3845 MHz) and the variance homogeneity, pointing out that the frequency variation can be easily adjusted by the microcontroller. Based on these results, it can be concluded that the linearity deviations are acceptable for the envisioned application, whereas the small deviations can be compensated with the help of the control voltage table values.

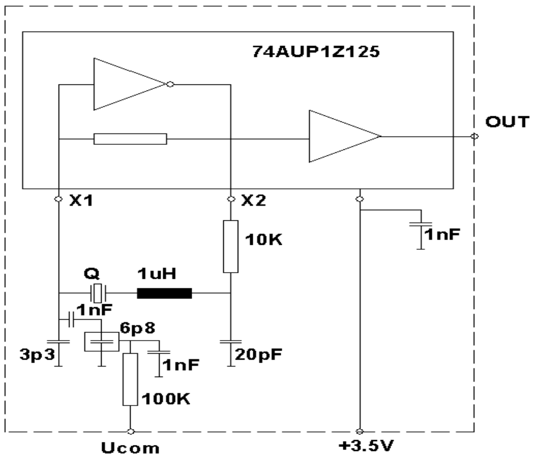

Figure 7. Voltage Controlled Crystal Oscillator schematic

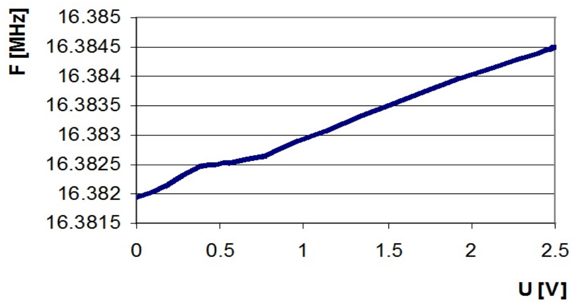

Figure 8. The Voltage Controlled Crystal Oscillator frequency variation as a function of the command voltage

Once the voltage control crystal oscillator is designed, it can be integrated in the active frequency stabilization oscillator circuit. The schematic of the active frequency stabilization oscillator is shown in Fig. 9. As previously mentioned, the design was developed considering serious power constrains, and thus, all the components were chosen in order to minimize the power consumption. So, the MSP430G2553 microcontroller, operating at 1 MHz clock has power consumption below 400 μA. Furthermore, besides other functions, the microcontroller includes an internal thermometer based on a diode and an internal analog to digital converter, which enables it to evaluate the temperature. Once the temperature is measured, the microcontroller commands the temperature variations compensation, expressed as a 10-bit value representing the compensation voltage. This command goes to the digital to analog converter (AD 5541), which will provide the BST capacitor with the suitable voltage required to compensate the temperature variation. To ensure the stability and the linearity of this voltage, an operational amplifier (AD8628) is used as a buffer for the voltage reference. The LM385 integrated circuit is used as a 2.5V reference voltage, and it was chosen considering its decent thermal stability and the very low power consumption (i.e. tens of μA). Finally, the DAC outputs a 0 to 2.5V command voltage, having a 16 bits resolution, which is applied to the BST capacitor. The entire assembly was placed in a 0.5 mm thick PCB box, in order to ensure its mechanical stability and the electrical shielding.

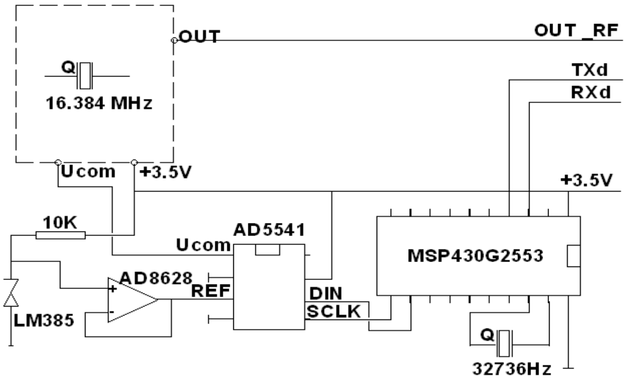

Figure 9. The schematic of the active frequency stabilization oscillator

B. Active frequency stabilization oscillator verification and results discussion

The first verification of the design aimed to determine the voltage variation as a function of the CPU temperature variation. Normally, this variation is linear, having a specific slope and a specific offset. However, for applications that require improved accuracy, this graph should be tested for each microcontroller and thus, it should be readjusted. As shown in Fig. 10, in this particular case, the microcontroller graph has a slope of 1.6363 and an offset of 394.91. It should be mentioned here that the exact determination of these values contributes to a more precise temperature determination. Next, in order to test the temperature reading precision, the speed of the temperature variation inside the chip for an abrupt change in ambient temperature was also tested. The results presented in Fig. 11 show that for accurate measurements waiting times of about 5 minutes are required. Nevertheless, for the envisioned applications, the temperature change is a rather slow phenomenon, whereas if necessary, this time could be further reduced by using materials that would ensure a faster thermal transfer toward the oscillator elements. The next step in the implementation of the compensation table was the frequency variation measurement for the uncompensated oscillator, as a function of the temperature (Fig. 8). For these measurements the control voltage was fixed at 1.25 V, in the middle of the variation range. A certain non-linearity is again observed, whereas the characteristic curve is approximately the one of an AT crystal cut (according to Fig. 1) and a Δθ angle between 0 and -1 Δθ degrees.

The correction table contains the control voltage values, represented as 16-bit numbers, in correspondence with the temperatures measured on 10-bit ADC (with a resolution of 0.611° C). In this specific case, the frequency compensation can be achieved in the temperature range of -2.5 to 87° C. Beyond this interval, experimental measurements have showed a frequency variation of 30 Hz for a 0.611° C temperature variation. An extension of the temperature range can be achieved by using two 6.8 pF STPTIC capacitors in parallel and by slightly adjusting the oscillator design.

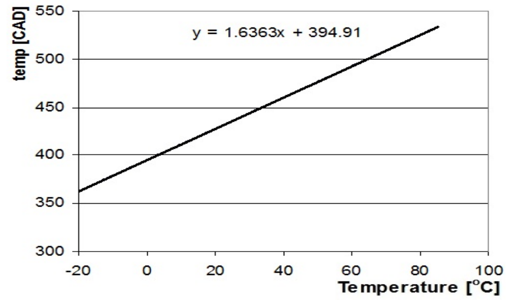

Figure 10. The CPU voltage variation as a function of the CPU temperature

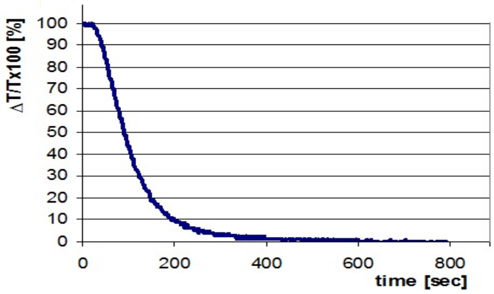

Figure 11. Internal temperature variation in time for an abrupt change in ambient temperature

The final step in the evaluation process consists in the experimental verification of the active frequency stabilization oscillator and in results comparison with respect to the uncompensated oscillator. This step involved analyzing the circuit behavior in a temperature range between 10-77° C. As illustrated in Fig. 12, the proposed design is very effective in terms of frequency stabilization. Thus, the active stabilization oscillator shows a frequency variation of only 86 Hz (5.2 ppm), whereas the uncompensated oscillator has a frequency variation of 1100 Hz (67 ppm). Furthermore, the results of the temperature compensated design can be further improved by recalculating the microcontroller coefficients table and by adjusting the voltage compensation coefficients. In such a case, the proposed method has the potential to stabilize the frequency within a 33 Hz limit (2ppm).

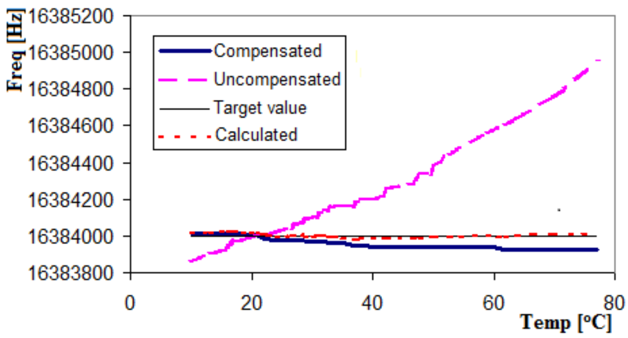

Figure 12. Frequency variation as a function of temperature for the non-compensated and for the active compensated oscillator

It should be mentioned that within the selected temperature interval, the existing industrial oscillators may have frequency stability of 5-7 ppm. These performances significantly outclass the ones of the uncompensated oscillator, whereas the proposed compensation method makes the two solutions similar in terms of frequency stability. However, a rather low performance oscillator has been selected especially to emphasize the suitability of the proposed method to improve the stability of an oscillator. Thus, it is expected that proposed method is able to provide a similar improvement rate even for an enhanced performance oscillator. Furthermore, the proposed method is able to compensate the quartz crystal aging (approx. 3ppm/year) ensuring enhanced performances and a longer lifetime. Additionally, the method ensures low energy consumption (similar to an uncompensated oscillator) being suitable for applications in which this condition is essential.

V. CONCLUSIONS

This article has addressed the problem of frequency stabilization under the influence of strong temperature variations. Thus, this article has presented a method able to achieve thermal stabilization for an oscillator envisioned to be used in vehicular communication applications. The proposed system achieves frequency stabilization in variable temperature conditions with the help of a microcontroller which measures the temperature and controls the frequency. Furthermore, the proposed design could be also used to stabilize frequency sliding caused by crystal aging.

The first experimental results were obtained using an industrial TCXO oscillator and were aimed to confirm the hypothesis according to which a BST capacitor can provide significantly enhanced performances compared to a varicap diode. Thus, these initial results have showed that the usage of the BST capacitor provided better frequency stability and also a wide frequency control range. The industrial TCXO was subsequently replaced with a circuit specially designed for enhanced frequency stability in temperature variable conditions and for low power consumption applications. Comprehensive laboratory measurements were the basis for generating the command table used by the microcontroller to compensate the frequency variation. After the design was completed, the performances were evaluated and compared to the ones of the uncompensated oscillator. Thus, the experimental results performed in a wide temperature range completely proved the viability of the proposed concept, and have showed that frequency stability is achieved within variable temperature conditions.

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