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RF oscillators stabilized by temperature compensated HBARs based on LiNbO₃/Quartz combination

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Abstract—In this work, we develop a radio-frequency oscillator operating near the 434MHz-centered ISM band to validate the temperature compensated capability of HBAR based on combining LiNbO₃ and Quartz single crystal plates for such purposes. Electrical and thermoelectric characterizations have shown QF product in excess of 10¹³ and a third order frequency-temperature behavior. A phase noise better than -160dBc/Hz at 100kHz has been measured as well as a -165dBc/Hz level at 1MHz from the carrier. First results showing that the resonator stability is better than 10⁻⁹ under room conditions. Further work is expected to lower that level well below 10⁻¹⁰.

I. INTRODUCTION

Radio-Frequency (RF) oscillators can be stabilized by various resonating devices. Their stability is mainly conditioned by the spectral quality of the resonator even if the oscillator loop electronics must be optimized to lower the generated noise as much as possible. For mid-term stability, temperature compensation as a key point and allows for notably improving the corresponding figure of merit. In a previous work [1], we have shown the possibility to build temperature compensated High overtone Bulk Acoustic Resonators (HBARs) combining LiNbO₃ and Quartz single crystal plates for the excitation of high order modes exhibiting cubic frequency-temperature behavior. In this work, we develop a radio-frequency oscillator operating near the 434 MHz-centered ISM band to validate the capability of the above-mentioned HBAR for such purposes. The composite substrate have been built using a 3-inch (YXl)/163° LiNbO₃ cut wafer bounded and thinned down to 15 μm onto a 350μm thick (YXl)/34°/90° quartz base.

Single-port resonators operating near 434 MHz (exploiting the third harmonic of the thinned niobate plate as the HBAR transducer) have been then manufactured. Electrical and thermoelectric characterizations have shown quality factor of the resonance in excess of 25000, yielding a QF product in

excess of 10¹³ and a third order frequency-temperature behavior. A SAW filter was used to select the ISM band and to filter the high spectral density HBAR response. The oscillator then has been measured using a phase noise automatic bench (R&S FSUP26 spectrum and phase noise analyzer). A phase noise better than -160dBc/Hz at 100kHz has been measured as well as a -165dBc/Hz level at 1MHz from the carrier. Mid term stability also have been achieved, first results showing resonator stability better than 10⁻⁹ under room conditions. Further work are expected to lower that level well below 10⁻¹⁰.

The first section of the paper discusses the design of the resonator based on thermoelastic computation of the temperature coefficients of frequency (TCF) of each mode of the structure. The basic theory is first recalled and general relations are provided to select the material stack thicknesses for a given mode order/frequency operating condition. A very brief description of the device fabrication is provided and experimental characterization of the resonators is reported. The oscillator architecture is depicted and the stability measurements detailed. As a conclusion, comparison with SAW-based oscillator is achieved and possible improvements of the oscillator is discussed

II. DEVICE ANALYSIS AND DESIGN

A. HBAR Temperature Coefficient of Frequency (TCF)

The celebrated Campbell&Jones method [2] is used here for predicting the TCF of any mode of a given HBAR. As it has been reported hundred times in previous papers, only the main basic equation is reported below:

$$f = \frac{V}{2e} \rightarrow \frac{df}{f} (T) = \frac{dV}{V} (T) - \frac{de}{e} (T) \quad (1)$$

which means that the frequency changes due to temperature variations are computed as the difference between the development of the velocity and of the stack thickness vs temperature. As discussed in [1], Lithium Niobate and Quartz have been associated for the fabrication of shear-waver based HBARs. LiNbO_3 provides crystal orientations for which very strongly coupled shear waves exist (k_t^2 in excess of 45%) whereas AT cut of Quartz allows for compensating second order frequency-temperature effects [3]. Although this idea was already proposed using other material combinations [4], no real design process was presented until now and therefore the possibility to actually determine structures allowing for high frequency operation with first order TCF smaller than 1ppm.K^{-1} was quite hypothetical. Second order compensation was even not imagined in [4]. Figure 1 shows the evolution of the TCF_1 of almost all the modes of thinned $(\text{YXl})/163^\circ$ LiNbO_3 layer atop a $(\text{YXlt})/36^\circ/90^\circ$ Quartz plate for various Niobate/Quartz thickness ratios, always assuming a Niobate layer much thinner than the Quartz substrate (which allows for neglecting the differential thermoelastic stress within the stack). One can see that depending on the harmonic number, the TCF_1 changes from +1 to -14ppm.K^{-1} . Furthermore, depending on the harmonic of the transducer alone, the TCF_1 may notably change and thus it cannot be considered as a simple periodic function vs harmonic number. Therefore, it is mandatory to accurately consider all the actual feature of the structure for an accurate design of a resonator, i.e. the operation frequency, the harmonic number and the thickness ratio for a given structure. To complete this, one should also account for the actual thickness of the device as this parameter will control the possibility to select one (frequency/harmonic number) couple. Finally, it clearly appears that the analysis of such HBAR TCF requires a numerical analysis and that if an intuitive approach allows for a first order definition of crystal orientations, the complicated distribution of energy within the stack vs all the structure parameters induces more intrication in the design process.

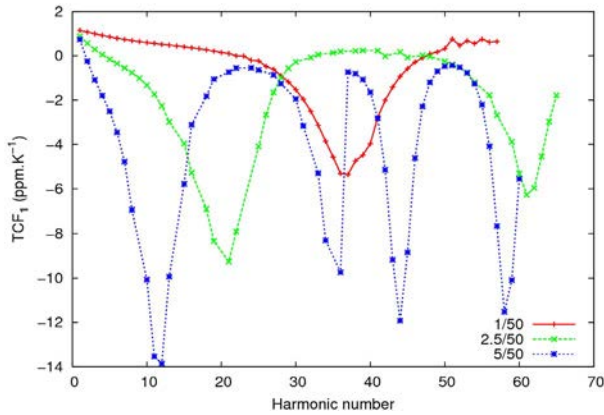


Figure 1. Plot of the TCF of a HBAR built on a $(\text{YXl})/163^\circ$ LiNbO_3 thinned plate bonded on $(\text{YXlt})/36/90$ Quartz substrate for various Niobate/Quartz thickness ratio (Quartz thickness arbitrary fixed to $50\mu\text{m}$)

As an illustration of these considerations, the evolution of the TCF of the most strongly coupled mode of the structure (coinciding with the fundamental mode of the niobate plate alone) has been plotted vs niobate thickness (Fig.2). A TCF_1 vs Niobate/Quartz ratio law has been derived from this curve, yielding the following expression:

$$\text{TCF}_1 = 42.5 \times R_t + 3.2 \times \log(200 R_t) \quad (2)$$

where R_t is the Niobate/Quartz ratio, thicknesses and TCF_1 being expressed in μm and in ppm.K^{-1} implicitly.

Considering now the TCF_1 evolution vs quartz cut angle θ (rotation around X axis), one can set the following complementary law:

$$\text{TCF}_1 = (\theta - 35) \times 5 \cdot 10^{-6} \quad (3)$$

Using these relations allows one to show that the most coupled mode of the structure is temperature compensated for $R_t = 1/50$ for the $(\text{YXlt})/34^\circ/90^\circ$ quartz cut, whereas the $(\text{YXlt})/33^\circ/90^\circ$ and $(\text{YXlt})/32^\circ/90^\circ$ cuts will be selected for R_t respectively equal to $2.5/50$ and $5/50$.

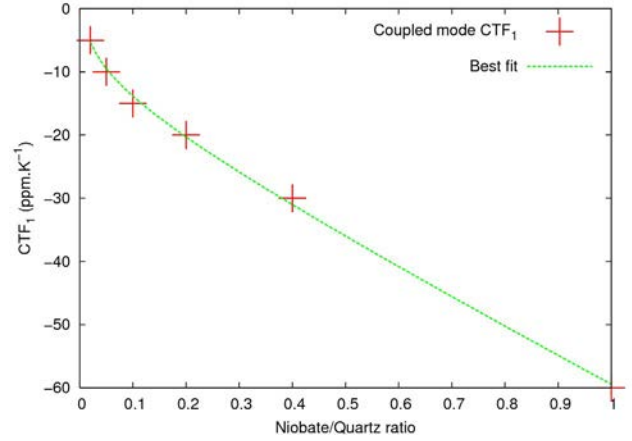


Figure 2. Plot of the TCF of a HBAR built on a $(\text{YXl})/163^\circ$ LiNbO_3 thinned plate bonded on $(\text{YXlt})/36/90$ Quartz substrate for various Niobate/Quartz thickness ratio (Quartz thickness arbitrary fixed to $50\mu\text{m}$)

B. 434 MHz resonator design

The design of the 434 MHz centered resonator has been done considering our capability to thin down LiNbO_3 wafers. A typical thickness of $15\mu\text{m} \pm 2\mu\text{m}$ then must be considered, the Quartz thickness being deduced along the theoretical analysis presented above. Assuming a phase velocity of the shear mode in the LiNbO_3 layer near 4000m.s^{-1} , the third harmonic of the fundamental mode then is easily excited at the expected frequency. To achieve the temperature compensation of the mode, the quartz cut angle and plate thickness then has to be fixed. A R_t value of $2.5/50$ is considered as a trade-off between the spectral density of modes and the ease to manufacture the material stack.

Consequently, the quartz thickness is found near $270\mu\text{m}$ for a cut angle corresponding to $(\text{YXl}t)/34^\circ/90^\circ$. Once again for manufacture simplicity, standard quartz wafer thicknesses are considered, yielding a value of $350\mu\text{m}$. The LiNbO_3 thickness then is adjusted to $14\mu\text{m}$ according to the above considerations (R_t actual value $2/50$). Validation of such a configuration has been achieved theoretically by computing the admittance of the corresponding device and then its theoretical TCF. An equivalent quality coefficient Q of 20,000 has been considered for Quartz whereas a Q of 100,000 was affected to LiNbO_3 . Au electrodes are used at the interface ($t = 300\text{nm}$, $Q \sim 1000$) and Al ones at the top surface ($t = 250\text{nm}$, $Q \sim 2000$). An effective Q value slightly larger than 20,000 then is predicted for a k_p^2 of 1.9% (Fig.3). Temperature compensation is checked by plotting both TCF_1 and second order TCF_2 for each resonance near 434MHz , as shown in Fig.4. For such a configuration, one can see that TCF_1 smaller than $1\text{ppm} \cdot \text{K}^{-1}$ can be obtained together with TCF_2 of less than $5\text{ppb} \cdot \text{K}^{-2}$.

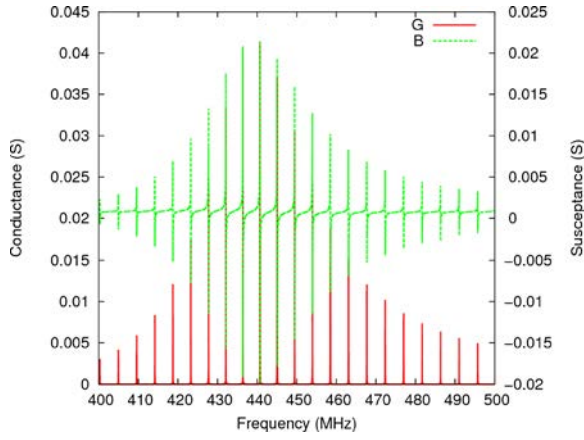


Figure 3. Theoretical admittance of a HBAR built on a $14\mu\text{m}$ thick $(\text{YXl})/163^\circ \text{LiNbO}_3$ plate onto $350\mu\text{m}$ thick $(\text{YXl}t)/34^\circ/90^\circ$ Quartz

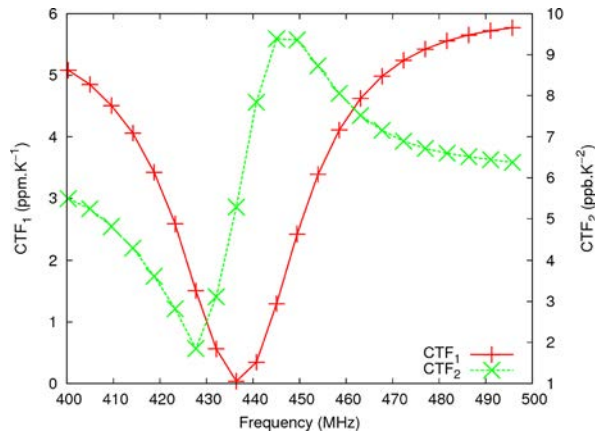


Figure 4. 1^{st} and 2^{nd} order TCF of the above $\text{LiNbO}_3/\text{Quartz}$ HBAR, temperature compensation achieved between 430 and 440MHz .

III. EXPERIMENTAL IMPLEMENTATION

A. HBAR fabrication

As mentioned above, only some information is reported here as most of the process has been already presented in details [1]. LiNbO_3 and Quartz are bonded together using thin Cr/Au films deposited on both wafer sides to be bonded and therefore used both as diffusion layers and interface electrode. A pre-bonding is first achieved using either an EVG bouncer or a Suss Microtech CL200 megasonic cleaner. The bonding then is reinforced by applying a quite strong homogeneous pressure during a few tenth minutes, yielding then an almost perfect acoustic adhesion between both material. Top electrodes are then deposited using standard lithography processes.

B. Resonator characterization

Conforming to the above design and manufacturing process, several devices have been fabricated and tested to select the most appropriate one for frequency stabilization in the ISM band. Figure 5 shows one example of resonator admittance from which electromechanical coupling k_p^2 and Q factor are deduced, respectively at about 0.2% and $25,946$, yielding a Q factor of 1.13×10^{13} , much better than Rayleigh wave based resonators on Quartz considering the same frequency. One can note that Q factor in excess of $30\,000$ also were measured (QF products in excess of 1.3×10^{13}), but for frequencies slightly out of the ISM band. The TCFs have been again tested to demonstrate the predicted compensation effect.

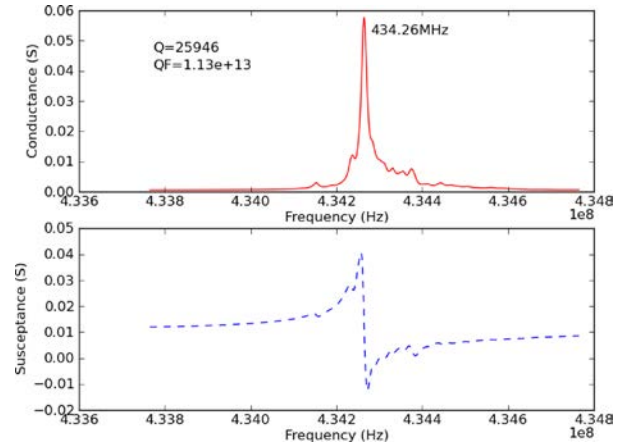


Figure 5. Experimental measurements (admittance) of a HBAR based on $(\text{YXl})/163^\circ \text{LiNbO}_3$ plate onto $350\mu\text{m}$ thick $(\text{YXl}t)/34^\circ/90^\circ$ Quartz

C. Oscillator stabilization

The implemented oscillator once again is very similar to what has been already presented for SAW devices [5] and therefore will not be detailed here. It is a Colpitts-type negative resistance circuit to which a buffer stage has been

added to isolate the oscillating loop and provide sufficient signal for the oscillator characterization. Figure 6 shows the characterization of the oscillator output using a spectrum analyzer, showing the definition of the resonance and also proving the possibility to actually select the ISM band by filtering.

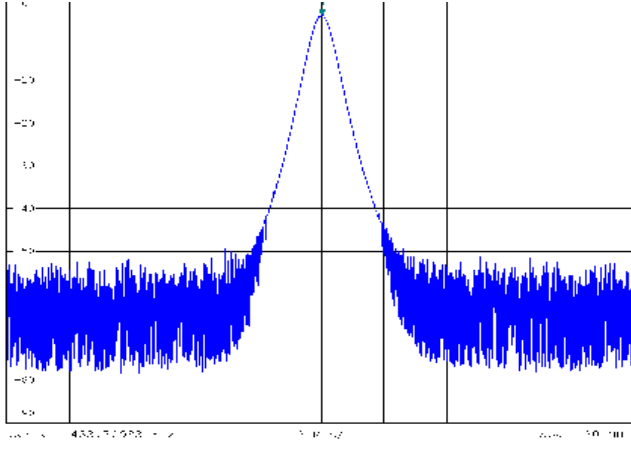


Figure 6. Spectrum of the oscillator output signal, close to the ISM center (433.7MHz)

Figure 7 shows the phase noise of the oscillator. The noise floor is at -165dBc/Hz and the phase noise at 10kHz is -140dBc/Hz.

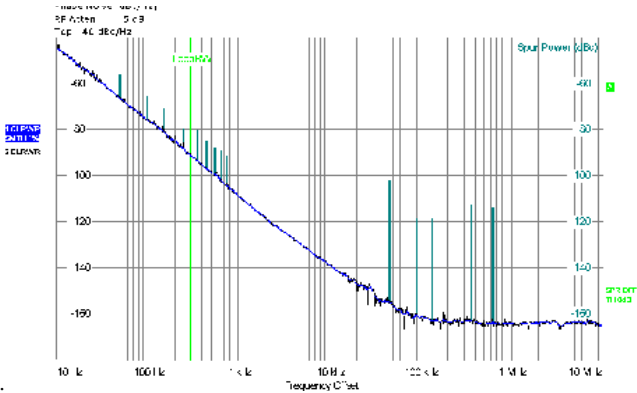


Figure 7. Phase noise of the Colpitts oscillator.

Figure 8 show Allan variance of the oscillator output signal. The oscillator based on HBAR temperature compensated presents a relative stability of near 2×10^{-10} over 2 seconds of integration at room conditions.

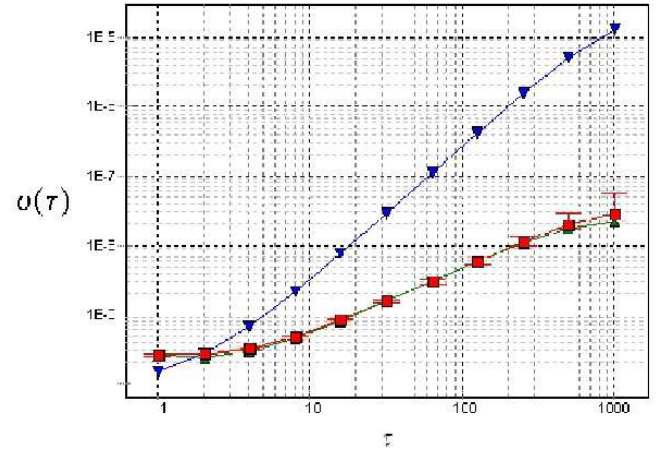


Figure 8. Allan Variance of the oscillator output signal, yielding a relative stability near 2×10^{-10} over 2 seconds of integration at room conditions

IV. CONCLUSION

In this work, we develop a radio-frequency oscillator operating near the 434MHz-centered ISM band to validate the temperature compensated capability of HBAR based on combining LiNbO3 and Quartz single crystal plates for such purposes. Electrical and thermoelectric characterizations have shown QF product in excess of 1013 and a third order frequency-temperature behavior. A phase noise better than -160dBc/Hz at 100kHz has been measured as well as a -165dBc/Hz level at 1MHz from the carrier. First results showing that the resonator stability is better than 10^{-9} under room conditions over 2 seconds. Further work is expected to lower that level well below 10^{-10} . To achieve this objective, excitation of resonator will be increase, test will be done under controlled temperature condition, and electromechanical coupling coefficient will be increase. Towards ultimate stability allows us competition with SAW based oscillators.

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