Experimental overtone modulation by adding external frequency in the oscillating loop of laterally coupled HBAR

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***Abstract*—In this paper, an innovative procedure of selection of the desired overtone of high overtone bulk acoustic resonator (HBAR) is experimentally presented. A composite resonator fabricated with $LiNbO_3$ on Quartz allows to demonstrate the principle of overtone modulation by adding in the loop an external frequency (f_i) or/and external voltage-controlled phase (φ_i). Consecutive HBAR overtones can be switched by voltage regulation of phase shifter device. Th voltage (V) can be adjusted so that the oscillator starts operating at the same desired overtone.**

Keywords — High-overtone Bulk Acoustic Resonators (HBAR) component; oscillator; frequency modulation, SAW filter, high quality factor (Q), overtone, single crystal.

I. INTRODUCTION

Low phase noise, small size and low energy consumption are prioritized for oscillators on RF domain. An increase in the quality factor (Q) of resonator, enables to improve phase noise of oscillators [1]. Recent progress in the development of resonators shows satisfactory performance. Technologies such as dielectric resonators [2], MEMS [3], SAW [4] and BAW, are being investigated for different applications. Among these technologies, HBAR resonator exhibits a Qxf product greater than $1x10^{14}$ (e.g., Q=68,000 at $f_0 \approx 1.6$GHz) [5], parameters which improve the oscillator performance.

Previous work has demonstrated excellent performances of HBAR resonator. As an example, an oscillator operating at 434MHz with low phase noise (-165dBc/Hz at 1MHz from the carrier) was fabricated using an HBAR resonator composed of crystal stack of $LiNbO_3$ and Quartz [6].

HBAR resonator presents a multitude of overtones. To develop an HBAR oscillator, one of the challenges is the effective selection of one of the overtones. W. Pang *et al*. has been implemented connection of FBAR to select one overtone at the frequency of 2.49GHz [7]. It is also possible to filter HBAR overtone with SAW filter, but the commercial SAW band-pass filter is not dedicated to this use and present bandwidths too wide to select just one overtone. So, the oscillator starts to one of the overtones in an uncontrolled manner due to initial conditions.

In this paper, we introduce an innovative principle for selecting or/and switching from unwanted overtone at desired overtone by adding, in the oscillator loop, an external frequency (f_i) or/and an external phase (φ_i).

II. HBAR RESSONATOR DESIGN AND MANUFACTURING

A. *Physical properties of HBAR resonator*

HBAR is a composite resonator which takes advantage of both acoustical substrate and piezoelectric materials. Figure 1, the piezoelectric material is sandwiched between two electrodes, which generates acoustical waves by the reverse piezoelectric effect. These waves are propagated inside the volume of the substrate and by the boundary conditions of materials, resonances frequencies are obtained. HBAR presents both odd and even overtones [8] [9] [10] [11].

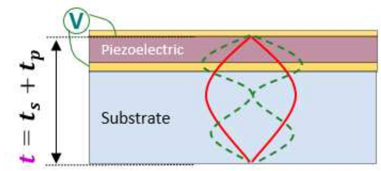

Figure 1. Principle of HBAR waves propagation within the stack. The HBAR structures is constituted of a top electrode, a piezoelectric material, a middle electrode, and an acoustical substrate.

B. *Manfacturing of HBAR resonator*

We fabricated HBAR resonators on two single crystals, which are bonded by gold deposition and with the standard process of MIMENTO facility. For experimentation, the selected structure of HBAR was constituted by a piezoelectric layer of (YX *l*)/163° - $LiNbO_3$ on acoustical substrate of (YX *lt*)/36°/90°-Quartz.

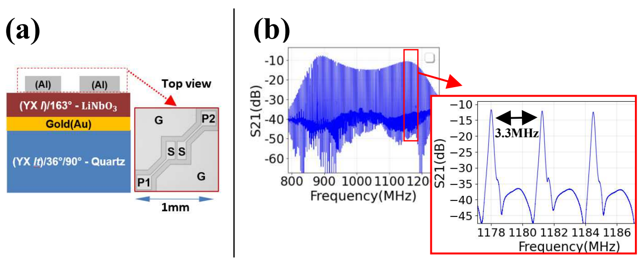

Figure 2: (a) Material stacks and top electrode parameters (P1: port one, P2: Port two, S: signal "effective electrode surface" and G: ground). (b) electrical measurement S21(dB) of one fabricated HBAR resonator.

Structure has already been studied by T. Baron *et al.* [6]. But, in this fabrication, the top electrode has been characterized to obtain a laterally coupled two-port resonator with electrical connection as Figure 2(a). Piezoelectric thickness (t_p) and substrate thickness (t_s) were also adapted to obtain resonance frequencies close to 1GHz as Figure 2(b).

This resonator exhibits a Qxf product of 8.13×10^{12} (*e.g.* Q=6,876 at $f_{n-1} \approx 1.1828$GHz), a CTF≈-5ppm/K, and a size of $0.5mm^3$. Its overtone separation is $\Delta f \approx 3.3$MHz.

III. PHYSICAL EXPERIMENTATION

the HBAR resonator was connected in series with SAW filter with 40MHz bandwidth (GSRFTA0582F). Then, a multitude of overtones has been filtered where the overtone (n) has the lowest insertion loss as Figure 3(a).

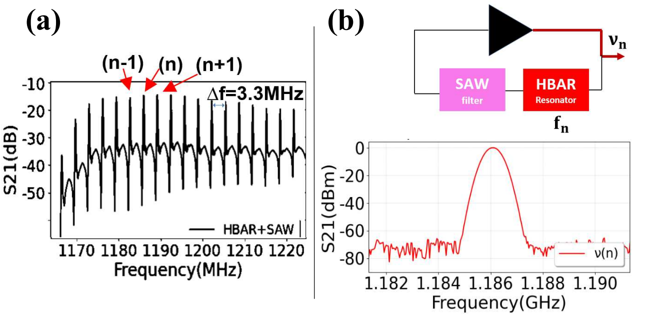

Figure 3: (a) electrical response of series connection of the HBAR resonator and SAW filter, (b) Initial operating frequency of oscillator at unwanted overtone (n)

The oscillator starts operating with unwanted overtone(n) at ν_n=1.186GHz as Figure 3(b). Measurement of this HBAR oscillator operating at ν_n=1.1828GHz exhibits a phase noise of -140dBc/Hz at 10kHz from carrier.

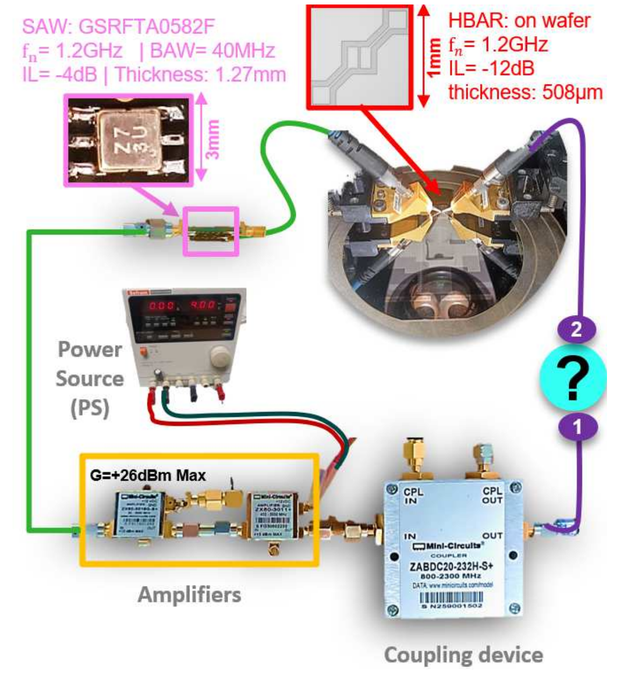

Figure 4: Experimental set up to demonstrate HBAR overtone selection by adding initial condition in the loop between the points 1 and 2. One HBAR resonator was selected on the wafer with more than two thousand resonators. Two amplifiers used to increase gain in the loop and coupling device introduced to read signal response.

Previous work demonstrated that HBAR quality factor increases with the number of overtones [9] [12]. So, it can be advantageous to select one desired overtone according to oscillator performance requirements. we therefore propose a principle to switch this undesired overtone (n) for one desired overtone, for example (n-1), by adding in the oscillator loop an external frequency or/and an external phase. Thus, modifying initial condition of oscillator loop.

Figure 4 shows the experimental set up where a series connection between one HBAR resonator and one commercial SAW filter has been configurated. Only one squared HBAR resonator was selected among those present on the 4-inch wafer diameter. We also connected two amplifiers to obtain a gain to compensate the insertion loss obtained in series connection on the Figure 3(a). Finally, to inject external frequency or/and phase, we connected a splitter or/and phase shifter device respectively. Power source is added to turned on/off the oscillator loop.

A. Frequency injection in the oscillator loop

External frequency (f_i) obtained from signal generator (SMA100B ROHDE&SCHWARZ) is injected in the loop through a splitter device (ZX10-2-12-S$^+$) between points 1 and 2 as the Figure 5(a). If f_i is close to one desired frequency of HBAR resonator, oscillator switches for this frequency. The unwanted overtone at ν_n=1.186GHz is switched for the wanted overtone at ν_{n-1}=1.182GHz when $f_i \approx f_{n-1}$ as Figure 5(b). Similar observation for the overtone (n+1), the unwanted overtone (n) at ν_n=1.186GHz is switched for the desired overtone at ν_{n+1}=1.189GHz.

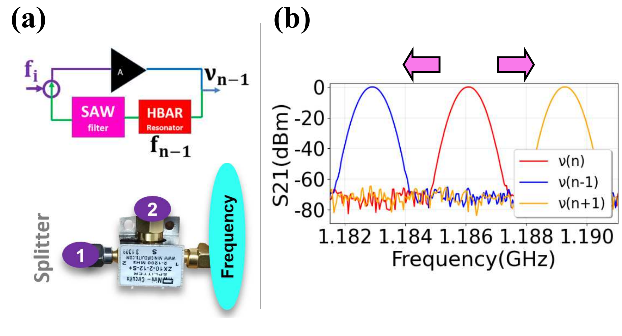

Figure 5: (a) Set up for adding frequency f_i in the loop by the splitter device between points 1 and 2. (b) Electrical response of oscillator where unwanted overtone (n) is switched for another desired overtone (n-1) or (n+1) following the initial condition of f_i.

Finally, the oscillator frequency (ν_{n-1}) or (ν_{n-1}) stays fixe and stable at this desired overtone (n-1) or (n+1) respectively when the added frequency (f_i) is removed from the loop by turning off the signal generator.

B. Phase injection in the oscillator loop

External phase (φ_i) is generated by voltage-controlled phase shifter device (JSPHS-1000) for frequencies between 700MHz and 1GHz as Figure 6(a). For this test, the SAW filter (GSRFTA0582F) was changed for another filter (ZW75BP-1034-S$^+$) with operating frequencies from 978MHz to 1034MHz due to phase shifter operating range. The voltage (V) is piloted by the power source (Sefram DC power supply PW18-1T). The phase shifter is connected between the points 1 and 2 of Figure 4. For experimentation the splitter can be removed or left on.

Oscillator loop was tested on two initial conditions.

In the first condition the oscillator is permanently turned on. Power source provides energy to oscillator, and it start oscillating with unwanted overtone (n) at ν_n=941.22MHz. The voltage (V) is gradually varied from V=0 to V=14V with step of 1V. We have found the oscillator operates with unwanted overtone (n) from V=0V until a voltage around V≈3.37V, after this value the overtone is switched for next frequency at ν_{n+1}=944.52MHz. Oscillator stays fixe at desired overtone for a range of voltage, which follows the yellow steps in the Figure 6(b).

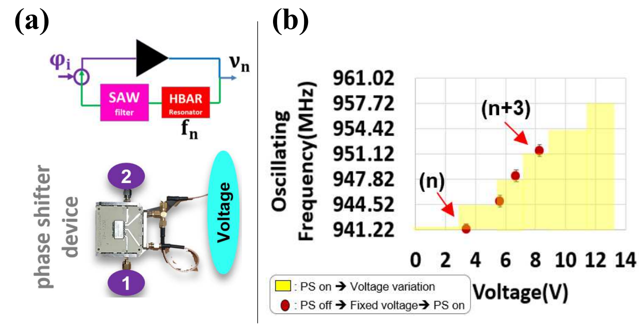

Figure 6: (a) Set up for phase injection in the loop. The phase shifter device is piloted by the external voltage V. (b) Overtone frequency variation according to voltage regulation following the first (yellow) and the second (red) oscillator conditions respectively.

The second oscillator condition is when oscillator is turned off and the voltage (V) is fixed at corresponding value as red point in the Figure 6(b). After that, the oscillator is turned on, the operating frequency starts at desired overtone. For instance, the oscillator starts with the desired overtone at ν_{n+1}=944.52MHz for a voltage of V=5.58V when loop is turned on. Therefore, we can fix the initial voltage (V) to start with desired overtone when oscillator is turned on.

Experiments prove with this two-oscillating conditions, oscillator loop can start operating with the desired overtone and it can be also switched for another wanted overtone.

IV. Conclusions and Perspectives

For a multitude of filtered HBAR overtones, the selection of only one desired overtone has been proved by adding initial condition of a frequency (f_i) or/and a phase (φ_i) in the oscillator loop.

The injection of frequency (f_i) enables to select desired overtone when oscillator start with unwanted overtone. The oscillator frequency stays fixe and stable when this injected frequency (f_i) is removed from the oscillator loop.

The injection of voltage-controlled phase (φ_i) enables to switch between consecutive overtones when oscillator is turned on. This voltage can be also regulated to start with the desired frequency before turning on the oscillator.

In conclusion, HBAR modulation is advantageous for applications which require to maintain and/or to switch frequency during oscillator operation in different conditions.

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