Phase Noise in Detached Crystal Oscillators

Luc A. Omlin
Corso G. Ferraris 111 Turin Italy
e-mail l.omlin@virgilio.it

***Abstract*—Progress made in the realization of 5Mhz Crystal Oscillators with "detached" Crystal. Presentation of phase noise measurements made in closed and open loop, which show a behavior which is, compared with conventional precision crystal oscillators, much closer to a plot of an ideal oscillator.**

I. INTRODUCTION

At the 1999 Joint Meeting EFTF - IFCS the author of this paper presented an alternative solution to sustain crystal oscillation, the "detached crystal oscillator" [1] and tried in the last years to improve the performance of such oscillators. Excellent stability results were attained and a different "behavior" of the crystal, compared with conventional precision crystal oscillators, was noted. To show this different behavior phase noise measurements in open and closed loop of the oscillator had to be made. It was therefore decided to build 2 test-oscillators (VA1 and VA2) with a horizontal all in one plane layout in order to have access to all the circuits in working conditions for eventual modifications of the oscillator parameter and eventual exchange of circuits. Only the crystal was temperature controlled in a very simple oven see Fig.6. The two 5MHz crystals used were with SC-cut in all glass holders with dimensions similar to HC6U; disassembled from compact, about 10 years old 5MHz OCXO's having only varicap-frequency adjustment. The first part of this paper shows the complete circuit of the oscillator and explains the reason of the choices made. The second part shows the phase-noise measurements with a detailed indication of the measurement set-up. This due to the fact that the results are unexpected and therefore subject to discussions of credibility.

II. OSCILLATOR CIRCUIT

The oscillator loop consists of: crystal - amplifier (3 stages) - "pulsgenerator" see Fig.1.

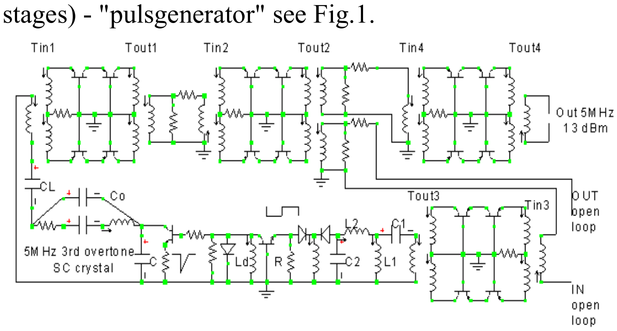


Figure 1. AC equivalent circuit of oscillator with "detached" crystal.

The pulsgenerator delivers to the crystal via a tank capacitor C, once every cycle (200ns) of the crystal oscillation, a short current pulse (about 10 to 20ns) out of a high impedance source (non saturated transistor) which restores the energy lost during the previous cycle in the losses of the crystal. After the end of this pulse the crystal with its tank-capacitor are detached from the pulse-generator for the whole rest (about 190 to 180ns) of the cycle (pulse delivering current source is off). The start time of this pulse is dictated by the zero crossing of the crystal current which is detected in the first amplifier stage; the crystal current flows through the very low input-impedance of the first amplifier stage (about 2 to 4 Ohms) in series with the crystal to ground. The crystal current is amplified in three amplifier stages and fed to the pulsgenerator. The Oscillator Output stage is driven by the second amplifier stage.

A. Amplifier Stages

The 3 amplifier stages are making part of the oscillator loop and have therefore a direct influence on the stability of the whole oscillator. This makes the requested features many and in consequence difficult to reach. The most important ones are:

- Low noise at a gain of about 25 to 35 dB (gain depends of crystal excitation level and losses in the pulsegenerator)
- At oscillator frequency a phase relationship between output signal and input signal phase which has to be repeatable and reproducible and independent of signal level and temperature
- Excellent back isolation which excludes the use of feedback
- No adjustments because of mechanical instabilities
- Good rejection of power supply noise
- Low power consumption because mounted normally in the oven
- Low up conversion of parametric noise (noise due to unstable bias down to DC)
- Low input impedance at least for the 1st stage

The author had best results meeting the mentioned features with a differential push-pull configuration, but the difficulty was the availability of well DC-matched (low drift) RF-transistors. To solve the problem of availability a very low drift LF-transistor pair was connected in cascode with a pair of unmatched RF-transistors. Also the differential LF pair is working in common base, this fulfils well the low input impedance feature and the good back isolation.

B. Pulse generator

The most critical building block of the detached crystal oscillator. The last version used is presented in this paper. It uses Schottkydiodes for the detection of the zero crossing of the input signal - the amplified crystal current. Such circuit is used for low noise frequency multipliers [2], before a circuit as described in [3] was used. Both work but both have disadvantages in this application. The Schottky diodes version needs a high input power (about 13 dBm). This power can be less if an series LC resonant circuit is used at the input [2], but such circuit introduces a 90 degree phase change. The other circuit has a big offset which translates in a static phase shift, which is tolerable but has to be compensated by an opposite phase shift somewhere in the loop. Further to produce the energy restoring pulse, the pulse generator should have the action to limit the signal level in the loop. This is now done by limiting the differentiated pulse, but disciplining a differentiated pulse is not a good idea. Better ideas are welcome by the author, taking in consideration that the source delivering the pulse to charge the tank capacitor (in series with the crystal) at the output of the generator must be of high impedance during the pulse and after the pulse in off state (crystal loading).

III. DRIVE LEVEL OF THE CRYSTAL IN THE OSCILLATOR

This is a very important aspect in the detached crystal oscillator and quite different from the design goals of conventional oscillators. The dissipation in the crystal (in this case a 5MHz 3rd overtone SC with a Q of greater 2.3 million) has to stay below 2 to 4 microwatts. This can be measured with a NA sweeping slowly through the resonance frequency of the crystal in open loop of the oscillator increasing after each run the crystal dissipation. When the dissipation is too high the gain curve becomes asymmetrical at the top and the phase curve does not stay in the point of highest slope, it shifts rapidly away to a higher phase value giving the impression that the Q is higher at a frequency away from fs. For the phase noise measurements shown below the dissipation of the crystals is less 1 microwatt. To use the detached crystal oscillator in open loop is a very easy to use and precise system to measure the crystal parameters.

IV. LOADED INCIRCUIT Q OF THE CRYSTAL

Being the afterwards shown phase-noise-plots of uncommon trend the results of the measurements of the loaded Q of the crystals are presented: In open-loop of the oscillators, having the output of the oscillators connected to a scope in scan mode (100ms/div). The driving pilot OCXO was interrupted for a short time; in Fig.2 you can see an interruption time of 184ms. From the envelope of the decay one can calculate the Q's: they are 2.3 million each, big values compared with conventional oscillators and very close to the unloaded Q's of these crystals.

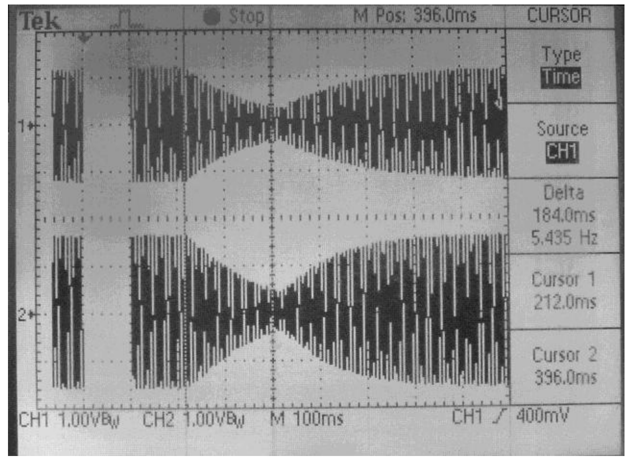
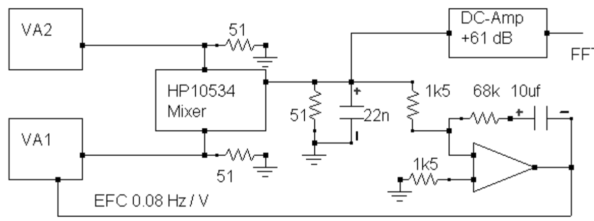


Figure 2. Loaded Q of the crystals.

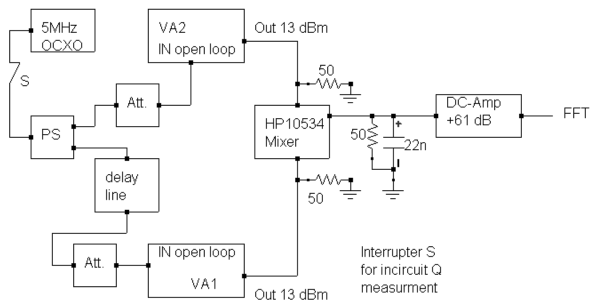
Another way to measure of the loaded incircuit Q is to measure the transfer function of the oscillator in open loop with a very long sweep time: the steepest slope of the phase curve gives the highest possible incircuit Q of the crystal used - this at the condition that when closing the loop, the oscillator works at the frequency where the highest Q was observed in open loop and without changing any impedance "seen" by the crystal in open and closed loop.

V. SET-UP FOR CLOSED AND OPEN-LOOP PHASE NOISE MEASUREMENTS

Unfortunately no test set which came in the last years on the market, where you just plug in the 2 oscillators needing no mixer nor a PLL and you don't care of the phase of the 2 oscillators, was at the disposition of the author. Fig.3 shows the Set-Up for closed loop and open loop. In closed loop mode the “OUT open loop” is connected to” IN open loop” (see Fig.1) via a step attenuator. The 61 dB DC-amplifier is identical to the one described in [4] but due to availability using the SSM2210 and 20 differential pair and working at higher gain. The analyzer is a HP 3561A set to: DC-input coupling, Hanning, narrow band, auto range off (after having found a range which allowed to make all measurement without overflow, and in the same range in order to overlay the plots), dB(V), Math Function SQRT (Mag^2)/BW. For commodity the main output amplifier (Tout4) was used for both open and closed loop as output amplifier driving the mixer because the level at open loop out is too low (about 0 dBm) to drive the mixer.



Setup CLOSED LOOP



Setup OPEN LOOP

Figure 3. Set-ups for phase noise measurements in closed and open loop of the two test oscillators VA1 and VA2

A. Measurement procedure used:

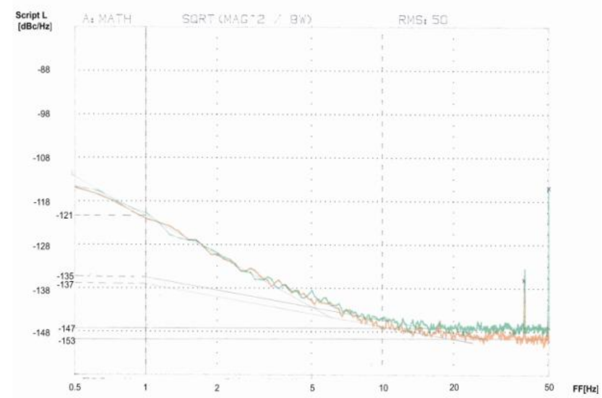
1st In closed loop but not yet connected to closed loop measurement set-up: frequency adjust the 3 oscillators, having the one you frequency control at a mid-range EFC level, to the same frequency (at least within 0,01Hz). Record frequency and Output level of the 2 Oscillators under test.

2^{nd} Set up for open loop measurement, adjust the attenuators to have the same level at the output of the 2 oscillators under test as recorded in step 1. If your output stages have the same static phase the 90degree delay-line should produce at the mixer inputs signals in exact quadrature, which can be controlled at the mixer (Z).

Very important is to have, when switching from open to closed loop, the same frequency (within 0.01Hz) without modifying the impedances seen by the crystal.

VI. PHASE NOISE MEASUREMENTS

Red curves are always for closed loop measurements, green ones for open loop measurements. Two plots are shown in Fig.4: one spans 2 decades (0.5Hz to 5Hz and 5Hz to 50 Hz), the other with higher resolution only the lowest decade (0.5 Hz to 5 Hz). Decades with higher FF are not shown because identical to the floor (f_0) starting at about 40 Hz. The high values for the floor are due to the low dissipation level (about 0.5 µW) in the crystal and the high loop amplification needed due to the high losses of the pulsegenerator. Very uncommon [5] is the behavior at 1 Hz and below. Instead to have a change in slope towards higher slopes (f_4) the slope decreases or continues with f_3. This is not due to measurement system roll-off, as can be seen from the PLL circuit in closed loop. The variation in slope from f_3 to quasi f_0 below 1 Hz from measurement to measurement is due to the long measurement time (about 15 minutes) during which oven instabilities can happen (it was a wrong decision to use a very simple oven) and in open loop further due to instabilities of the pilot OCXO within the bandwidth of the devices under test. Is the Leeson frequency at about 1Hz, which would be in agreement with the incircuit Q measurements shown in Fig.2 ?



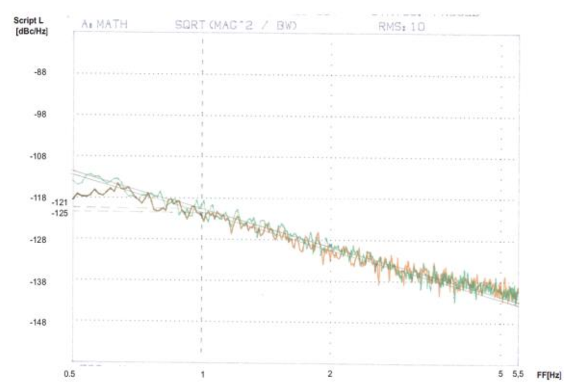


Figure 4. Phase noise measurements of test oscillators VA1 and VA2 in open loop and closed loop. Upper figure shows 2 decades and the lower figure shows the lowest decade with higher resolution

VII. TIME DOMAIN MEASUREMENTS

For completeness 2 graphs of 50 consecutive counter measurements are shown in Fig. 5. One with τ 1 sec the other with τ 150ms. One of the oscillators (VA 2) was measured against a selected OSA 8607 with time interval measurement of the beat (about 8 Hz) between the two oscillators. For τ 1 sec the Root Allen Variance (RAV) (elaborated by the counter) resulted to be 5,7 x 10^{-13} and for τ 150ms 8,3 x 10^{-13}. Interesting are the oscillations with a period of 5 to 10 sec which have also been observed with other detached crystal oscillators built in the past but with lower amplitudes. When measuring at start up of the oscillator, just before reaching the inversion point temperature these oscillations are not present or only in a very attenuated form and the RAV has better values (up to a factor of 2) compared with values at stable oven temperature. No explanation has been found up to now - it is like the need of the crystal of a small "braking" force.

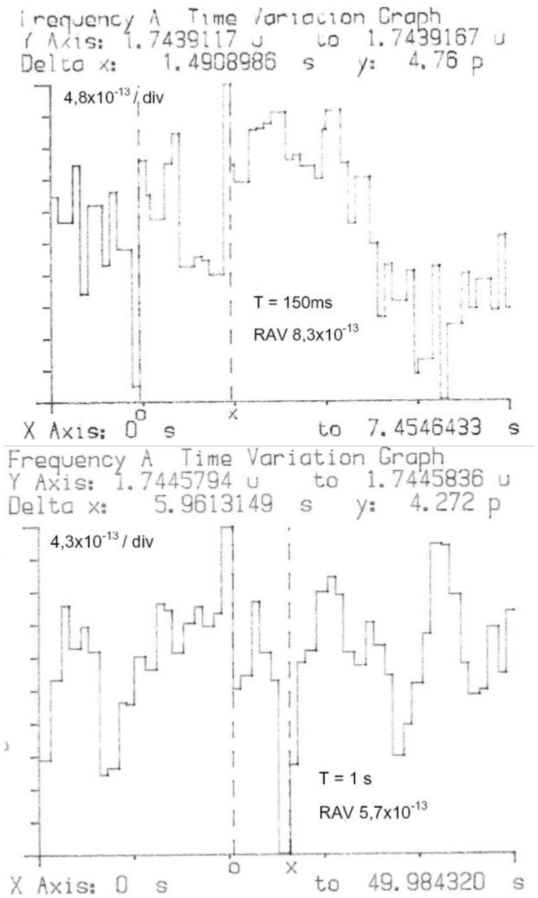


Figure 5. 50 consecutive time domain measurements of VA2. Upper figure for τ 150 ms, lower for τ 1 sec

Figure 6. Picture of the open test oscillator.

VIII. CONCLUSION

The phase noise measurement of these two simple detached crystal oscillators with "low end" precision crystals show that the state of art stability of crystal oscillators can be further improved when using the "detached crystal" sustaining method.

ACKNOWLEDGMENTS

Many thanks to Enrico Rubiola for the discussions on the subject of this paper, to Ivan Barla for finding substitution of broken instruments during the preparation of this paper, to Giancarlo Dappiano for the help in formatting this paper and to my family for having tolerated me during these last 4 very stressing months.

REFERENCES

[1] L. Omlin "New Sustaining Circuit for Precision Crystal Oscillators" Joint Meeting EFTF - IFCS 1999 pp. 401-403.

[2] C. Wenzel "New Topology Multiplier Generates Odd Harmonics" rf technology (year?)

[3] R. A. Baugh "Low Noise Frequency Multiplication" FCS 1972 pp 50-54

[4] E. Rubiola "Low flicker-noise amplifier for 50 Ohms sources" Review of Scientific Instruments Volume 75, Number 5, May 2004

[5] E. Rubiola "Phase Noise and Frequency Stability in Oscillators" Cambridge University Press 2009, ISBN 978-0-521-88677-2