ULTRA LOW NOISE SURFACE ACOUSTIC WAVE OSCILLATOR FOR INSTRUMENTATION MARKET

MICHEL CHOMIKI
TEMEX - 790 Avenue du Docteur Donat, 06250 Mougins, France
www.temex.com

Introduction

This paper presents a new TEMEX family of Ultra Low Noise (ULN) Surface Acoustic Wave (SAW) oscillators in the range of 300 to 600 MHz.

Figure 1 shows a typical phase noise measurement of such ULN SAW oscillator at 500 MHz featuring a noise floor of - 182 dBc/Hz. This characteristic is now measurable with the new noise spectrum analyzers, like DCNTS from Aeroflex, using cross correlation techniques to extract exact phase noise of a given oscillator from the measurements of a set of three similar oscillators.

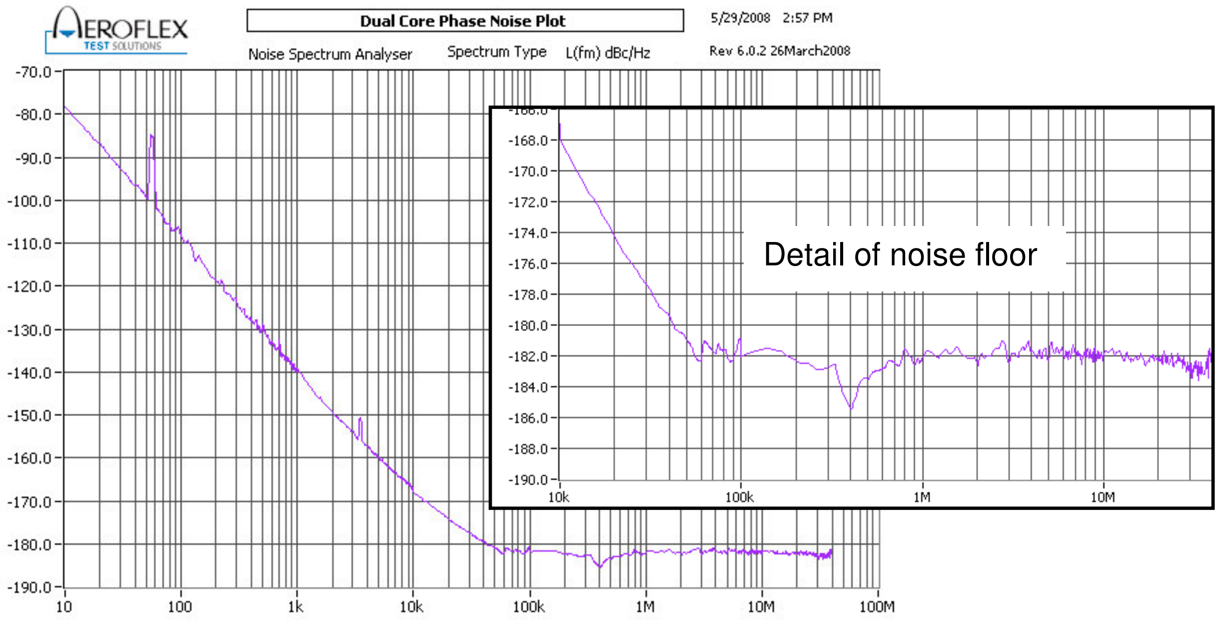

Figure 1: Phase noise of SAW oscillator at 500 MHz
(X axis: frequency offset in Hz, Y axis: spectral density of noise in dBc/Hz)

ULN SAW oscillators are proposed in two grades of packaging according to environmental conditions:

- Grade B for stabilized platform applications like instrumentation & test, radar simulation and ground based equipment,
- Grade D for airborne applications with harsh environmental conditions.

This paper is focusing on grade B and will address the following topics:

- Rationale of SAW Oscillators (SO),
- SAW oscillator: block diagram, description of each block, main characteristics,
- SAW resonator: description, high reliability design considerations, resonator design and manufacturing, flicker noise measurement test set-up,
- Phase noise measurement and simulation using Leeson’s model,
- Typical application.

Rationale of SAW oscillators

For decades Crystal Oscillators (XO) have been the unequaled references for stable and/or low noise frequency sources. This leadership is due to the high Q-factor achievable with Bulk Acoustic Waves (BAW) on quartz.

The resonant frequency of such crystal resonator is inversely proportional to the thickness of the quartz disk (the resonant cavity) and is today limited, by physical manufacturing constraints, to about 150 MHz. If the application needs a higher reference frequency, the XO frequency is multiplied. Doing this, the phase noise (in dBc/Hz) is degraded by at least 20 $\log_{10}$ (N), N being the multiplication ratio. This degradation limits directly the performance of the host system.

In order to avoid such limitation, the solution is to start with an oscillator at higher fundamental frequency. SAW technology on quartz offers this opportunity. With SAW, the resonant cavity size is not linked to the thickness of the substrate, like with BAW, but to the line resolution of the pattern deposited on its surface. With the standards of the microelectronic technology used for SAW (line resolution to 0.3 µm), resonant frequencies up to the GHz range are achievable.

To fix the improvement in phase noise gained by SAW technology, just compare, in table 1, state-of-the-art XO at 100 MHz multiplied by 5 and SO at 500 MHz for different frequency offsets. Close to the carrier XO is always the best but for offsets greater than 7 kHz, SO supersedes XO and the improvement reaches 14 dB on noise floor. This example introduces also the typical application which will be developed at the end of the paper.

Offset frequency (Hz)	**Phase noise at offset frequency (dBc/Hz)**			**Improvement due to SAW (dB)**
	Best XO at 100 MHz	**XO times 5 + 14 dB**	**SAW Oscillator at 500 MHz**	
10	- 105	- 91	- 78	
100	- 137	- 123	- 110	
1 k	- 163	- 149	- 140	
7 k	- 178	- 164	- 164	0
10 k	- 179	- 165	- 168	+ 3
100 k	- 182	- 168	- 182	+ 14
> 100 k	- 182	- 168	- 182	+ 14

Table 1: Comparison of XO & SO phase noises at the same frequency

SAW Oscillators

As already mentioned, two grades of packaging have been developed according to environmental conditions. These packaging are presented on figure 2.

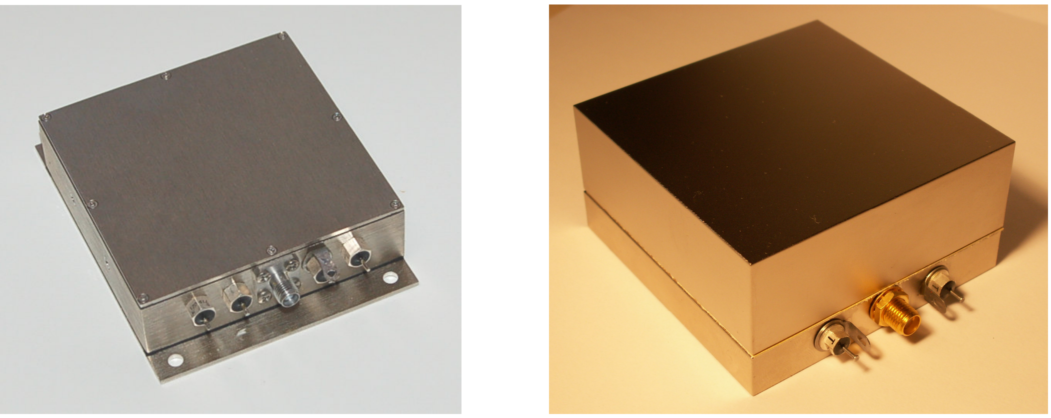

Figure 2: Grade B (left) & grade D (right) packaging

Why two grades? Phase noise measurement, as shown on figure 1, uses cross-correlation techniques between three similar oscillators in order to extract the exact phase noise of each individual oscillator. So for the measurement of one grade D oscillator it needs to have two other replicas of the same oscillator which may be grade D or a “low cost” solution. Mandatory are the same performances, but only at room temperature and quiet environment like grade B.
The oscillator block diagram of both grades is the same and is given on figure 3.
The differences are only on the assembly technologies used for the SAW resonator, the electronic circuitries and the packaging.

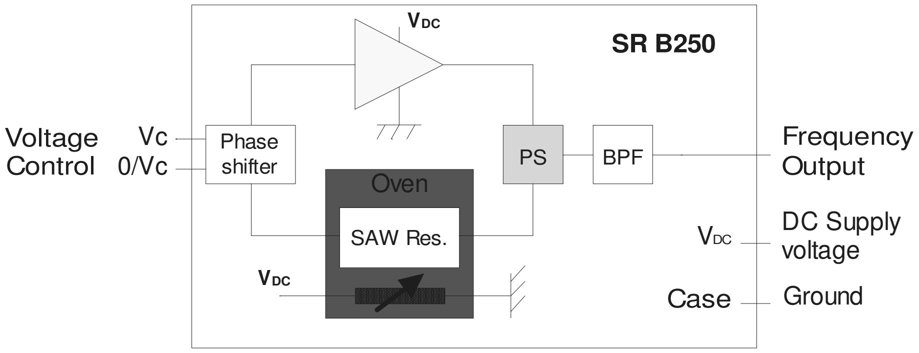

Figure 3: block diagram of the SAW oscillator

Table 2 gives electrical characteristics of a 500 MHz SO which are valid for grade B or grade D oscillators, but limited to a laboratory environment, e.g. for temperature in the range [- 20 to + 50 °C]. More information is available on Temex web site (www.temex.com).

Parameters	Unit	Minimum	Typical	Maximum
Frequency output (SMA Connector)				
Nominal frequency	MHz		500	
Output level (50 Ω load)	dBm	11.5	12.5	13.5
Harmonics suppression	dBc	-30		
Phase noise @ 1 kHz offset	dBc/Hz	-140	- 137	- 134
Phase noise @ 10 kHz offset	dBc/Hz	-168	- 165	- 162
Phase noise @ 100 kHz offset	dBc/Hz	-175	- 174	- 173
Phase noise floor	dBc/Hz	< -180	< - 178	- 175
VSWR	-		1.5:1	2:1
Free running mode (Voltage Control pin NC)				
Factory set accuracy @ 25 °C	ppm		± 0.2	± 0.5
Temperature stability	ppm			± 2
Aging per year	ppm			± 1
Electrical tuning (Voltage Control pin)				
Relative tuning range	ppm	± 2	± 3	
Voltage range	V_{DC}	3	4.7	7
Slope @ V control = 4.7 V	Hz / V	1000	1500	2200
DC supply voltage (DC supply voltage pin)				
Voltage range	V_{DC}	11.8	12	12.2
Supply current	mA		250 @ 25°C	600
Warm up time	mn		4	5

Table 2: electrical characteristics of SAW oscillator at 500 MHz

SAW resonator

The SAW resonator is a 2-port bi-directional passive device on quartz. Figure 4 shows the active face of the resonator with typical dimensions for the acoustic pattern. The resonator comprises two IDTs (Inter Digital Transducer) and a resonant cavity formed by two reflecting grating arrays.

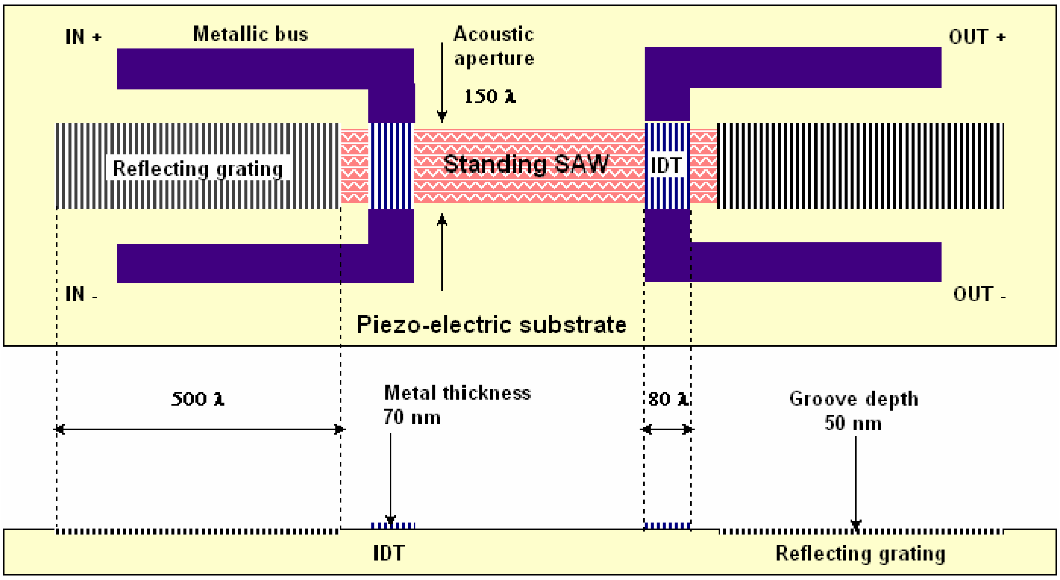

Figure 4: SAW resonator, top view and cross section

The electrical equivalent circuit is given on figure 5.

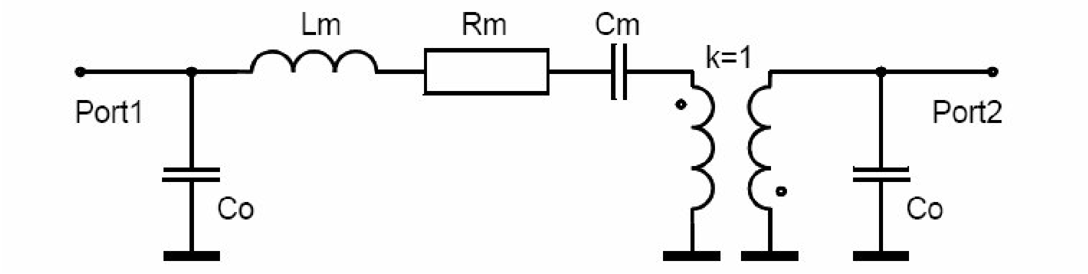

Figure 5: equivalent circuit of a 2-port SAW resonator with 180° phase shift

Typical values of R L C components at 500 MHz are as follows:

- Lm = 0.64 mH
- Rm= 100 Ω
- Cm= 0.16 fF
- C_0 = 1 – 3 pF

The electrical parameters of the resonator are as follows:

- Center frequency: F_0. Center frequency is defined by the application.
- Insertion loss: IL. IL is set to 6 dB (i.e. Rm = 100 Ω), this value minimizes phase noise.
- Q-factor: Q_u (unloaded) or Q_l (loaded) in a 50 Ω input/output network.
  Q-factor, IL and F_0 are linked by the following formulas:
  - $F_0 * Q_u = 1.10^{13}$ Hz. This characteristic is valid for grade SPQ (Special Premium Q) quartz substrate under vacuum conditions.

   - $Q_l = Q_u*(1 - 10^{-(IL/20)})$. At 500 MHz, Q_l is around 10.000.
- Maximum input power. + 23 dBm is achievable at 500 MHz.
- Flicker noise coefficient α_r.

Like active devices, the SAW resonator is the source of 1/f additive noise. There is no model describing the flicker noise on quartz. We only know some parameters which may affect this noise: quality of quartz, surface finishing and foundry process. We also know some "recipes" which may improve flicker noise: high temperature annealing or high input power driving for a short time.

Measurement of α_r is performed with a test set-up as shown on figure 6. The value of the coefficient is the phase noise at an offset frequency of 1 Hz.

A very large statistical distribution exists on this parameter even on resonators issued from the same manufacturing batch. ULN oscillators use resonators with a flicker noise coefficient smaller than 3.10^{-40} rad²/Hz. Larger values degrade close-in phase noise and explain most of the discrepancies revealed by unexpected bad phase noise measurements.

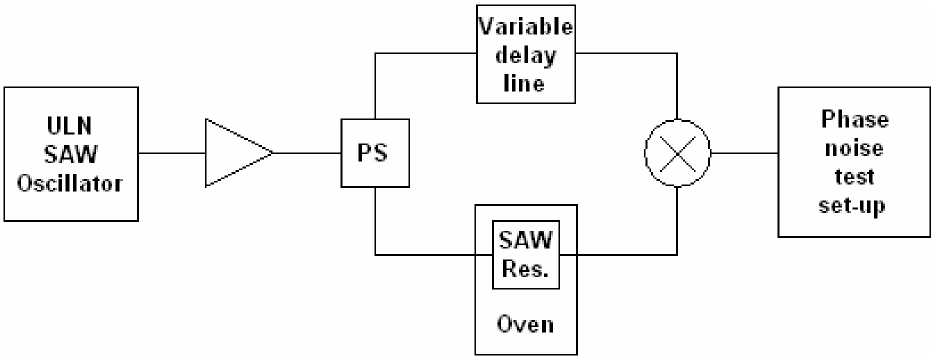

Figure 6: Test Set-up for flicker noise measurement

High reliability SAW resonator considerations

SAW resonators are on quartz for the same reasons than BAW resonators:

- Piezoelectric effect simplifies I/O electrical interfaces,
- High Q-factors are achievable with quartz substrate of high quality and under vacuum conditions,
- Frequency dependency versus temperature is low. The law is parabolic:

$$\Delta F/F = \alpha\,(T - T_0)^2$$

T_0 is the turnover temperature and is selected by the means of the cut angle of the quartz wafer. The value of coefficient α is circa – 3.10^{-8}/ °C². Oven control is mandatory for stable frequency application.

Low ageing is an important requirement for most applications. Ageing mechanisms are known: metallic migration into quartz, surface pollution by organic residues, etc.

So, to target low ageing characteristics, following design and process rules are of premium importance:

- Minimize metallic interface with quartz in the acoustic cavity: metallic transducers are necessary but cover a very small portion of the surface of the cavity (about 5 %). The main contributors are the reflecting arrays (30 % of the total surface of the cavity). It is why reflectors are gratings rather than metallic strips. The grating process is an extra step in the foundry process but the benefit is great.
- The cavity must be under vacuum conditions: this is mandatory to reach a maximum Q-factor, but it is also profitable for the ageing (no pollution by the medium in top of the substrate)
- No organic residues inside the cavity: resonators for grade B are housed in a similar enclosure as BAW resonators (cold weld technology under vacuum conditions after degassing process). This enclosure is not suitable for grade D due to vibrations

constraints. The solution, introduced 20 years ago, is the All Quartz Package (AQP). Limited to an individual resonator at its beginning, AQP process is now a collective process using Wafer Level Packaging (WLP) technology of quartz on quartz.

Leeson’s model and measurement

In 1966, Leeson proposed a model for the phase noise of a SAW oscillator as shown:

$$S_\Phi(fm) = \frac{\alpha_r f_0^{\,4}}{fm^3} + \frac{\alpha_e}{f_m^{\,3}} * \left(\frac{f_0}{2Q_L}\right)^2 + \frac{2\alpha_r Q_L f_0^{\,3}}{f_m^{\,2}} + \left(\frac{f_0}{2Q_L}\right)^2 * \frac{2GFkT}{P_0} * \frac{1}{f_m^{\,2}} + \frac{\alpha_E}{f_m} + \frac{2GFkT}{P_0}$$

- f_0 = oscillator nominal frequency
- f_m = offset frequency
- P_0 = power at the output of the loop amplifier
- G = gain within the loop
- F = noise figure of the loop amplifier
- k = Boltzman constant, $1.38\ 10^{-23}$ J/ K
- T = temperature in K
- Q_l = loaded Q-factor within the loop
- α_r = flicker noise coefficient of the SAW resonator
- α_e = flicker noise coefficient of the electronics (amplifier)

The measured phase noise is: $\mathscr{L}(f_m) = S_\Phi(f_m)/2$.

By introducing in the Leeson’s model the measured value of each term of the formula for the SAW oscillator shown in figure 1 we compute the red curve of figure 7 which fit very well with the measurement.
Thanks to the new test-set of Aeroflex, it is the first time that measurement and simulation fit so perfectly, confirming the pertinence of Leeson’s model.

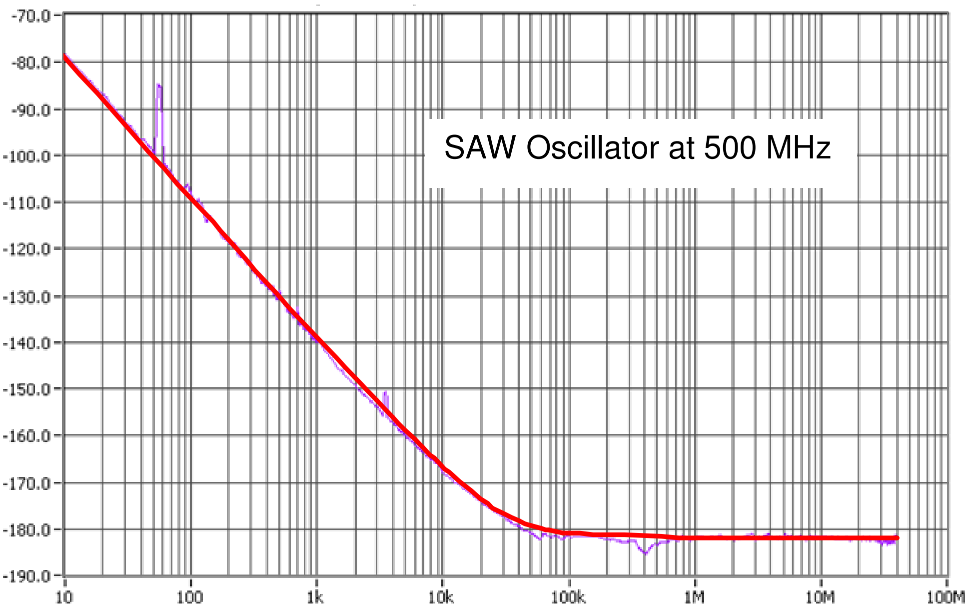

Figure 7: Phase noise measurement and Leeson’s model (in red) fit exactly

Typical application

A typical application of ULN SAW oscillator is the cleaning of the phase noise of microwave frequency sources for frequency offsets ranging from about 10 kHz to 1 MHz.
The improvement is around 15 dB or more.

The above mentioned frequency offset range is, for instance, the Doppler range of targets for airborne radars in X band. Any improvement in this range is directly linked with instantaneous dynamic range improvement or, in others words, improvement in detection of e.g. stealth targets.
The ULN microwave frequency source is the result of the cascade of several ULN oscillators at different frequencies phase locked each one on the others. Figure 8 shows a typical example of such a frequency source: a YIG oscillator is phase locked on a multiplied 100 MHz XO which is itself phase locked on a multiplied 10 MHz XO. The resulting phase noise is as shown on figure 8: close to the carrier the phase noise is coming from the 10 MHz ULN XO, then the phase noise is coming from the 100 MHz ULN XO and far from the carrier the phase noise is the free running phase noise of the YIG oscillator.

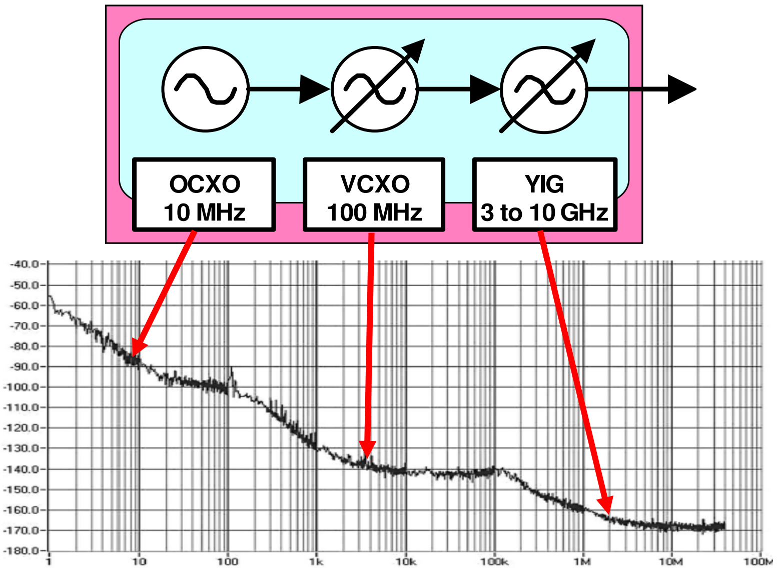

Figure 8: typical microwave source and its phase noise (here at 4.2 GHz)

By inserting an ULN SAW oscillator between the XO at 100 MHz and the YIG oscillator, the phase noise is improved by about 15 dB as shown in figure 9. This improvement requested by airborne application must also be implemented in instrumentation & test applications devoted for this market segment.

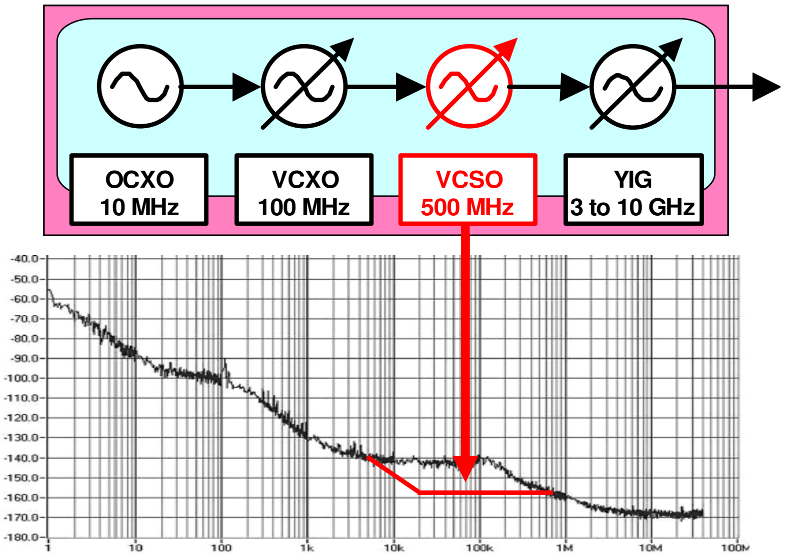

Figure 10: phase noise improvement by inserting a SAW oscillator at 500 MHz

Conclusion

This paper has presented the new ULN SAW oscillators family devoted for instrumentation and test application (grade B). This family is now completed with ULN SAW oscillators for military application (grade D). More information on existing products and available frequencies is on Temex web site (www.temex.com). ULN SAW oscillators achieve the lowest noise floor at RF frequencies. Typical demanding application is the cleaning of noise floor up to microwave frequencies either for military airborne radar or instrumentation & test equipment devoted to measure ultra low noise oscillators.