Performance Verification of Injection Locked STW Clocks with BAW Crystal Stability

I. D. Avramov[&] and J. Columbus[#]
[&]Institute of Solid State Physics, Sofia, Bulgaria
[#]Vectron International, Hudson, NH, USA

Abstract - **This work verifies the expected phase noise and medium-term stability improvement of recently proposed 1 GHz surface transverse wave (STW) injection locked clocks operating on 1.25V supply voltage with bulk acoustic wave (BAW) crystal stability. Compared to a free running STW oscillator, temperature stability improvement by a factor of 16 and close-in phase noise reduction by 18 to 25dB is demonstrated. A high-power version of the system consumes 90mA of DC current, generates 4dBm of output power at 1GHz and provides a thermal noise floor of -174dBc/Hz. A low-power version demonstrates safe lock and integrated r.m.s. jitter of 220 to 640fs over a (0 to +85)°C temperature range. Data on phase noise, output power and frequency sensitivities to supply voltage variations over temperature are provided and discussed. Ways for potential improvement of system performance are suggested.**

Keywords-injection locked oscillators; STW resonators; BAW crystals; comb spectrum oscillators, phase noise.

I. Introduction

Future developments of low-noise clocks in the lower GHz range require bulk acoustic wave (BAW) crystal stability and operation at supply voltages as low as 1.25V for compatibility with next generation CMOS technology which will operate on such low supply voltage for lower heat dissipation and larger integration scale on a unity chip area. Current surface acoustic wave (SAW) based oscillators (SAWO), often used as low-noise clocks, do not provide BAW crystal stability and need up to 500ppm tuning range to compensate for temperature induced frequency shifts over a (-45 to 85)°C temperature range and for fabrication tolerances in phase locked loop (PLL) systems. Such tuning ranges, typically realized with varactor controlled phase shifters, are very difficult to achieve if the tuning voltage is limited to 1.25V [1]. In addition, the thermal noise floor of SAW based PLL systems is too high for a variety of applications.

A recently proposed solution to these problems [2] avoids tuning and combines the temperature stability of a BAW crystal oscillator (XO) with the excellent phase noise performance achievable with surface transverse wave oscillators (STWO) operating on 1.25V supply voltage according to the nonlinear "step-up" converter principle [3-5]. Such a STWO is injection locked to a low-power high overtone of a XO controlled comb spectrum oscillator used as a reference. Over the locking bandwidth which is selected to be larger than the temperature induced frequency shift, the STW based injection locked oscillator (ILO) tracks the frequency of the XO reference and adopts its temperature stability which is by at least an order of magnitude better than in the free running STW oscillator. The ILO also adopts the better close-in phase noise of the XO overtone while retaining the high output power and low thermal noise floor of the STW oscillator [6].

This study presents experimental data verifying the overall phase noise and temperature stability improvement of practical 1GHz STW-based ILO prototypes operating on 1.25V supply voltage. It also provides and discusses data on frequency and power instabilities as well as phase noise and jitter sensitivities versus supply voltage and temperature variations.

II. Design Concept

A. Problems with SAW Based PLL Systems

Integrated PLL circuits are nowadays the easiest and most inexpensive way to stabilize the frequency of a free running SAW oscillator against temperature, supply voltage and load variations and make it as stable as the frequency of the BAW XO used as a crystal reference. This is achieved by making the SAW oscillator voltage tunable, (also known as voltage controlled surface wave oscillator (VCSO)), and by digitally dividing its frequency down to the frequency of the crystal reference at which a phase comparison is made by a phase detector (PD) circuit. If the divided SAW frequency differs from the frequency of the crystal reference, a correction voltage, generated by the PD, is used to tune the frequency of the VCSO until both signals become equal in frequency and phase. As soon as this is achieved, the VCSO remains phase locked to the crystal reference. The PLL bandwidth over which safe locking is achieved depends on the tuning bandwidth of the SAW oscillator and is typically 300 to 500 ppm to compensate for temperature induced frequency shifts over the (-40 to +85) deg. C operating range and for fabrication tolerances of the SAW device. Such large tuning ranges are very difficult to achieve if the tuning voltage is limited from (0 to 1.25)V since the capacitance change of the varactors used in the electronic phase shifters is very small and highly nonlinear in this tuning voltage range. One solution to the problem is to use a SAW device with a fairly low Q, such as a SAW delay line, to provide large tuning range with a small phase variation in the loop. However, low Q results in poor VCSO phase noise. Another option is to keep the Q reasonably high, using a SAW resonator device, and implement sophisticated phase shifters with a large number of varactors in the loop to achieve large phase variation range with a small tuning voltage [1]. This approach cannot provide sufficiently low phase noise either since varactors are active devices and, if used in large numbers, each of them adds to the flicker phase noise and degrades the overall noise performance accordingly [7].

The data plots in Fig. 1 represent a comparison of the phase noise performances of a commercially available SAW based PLL system at 500MHz and a free running 1GHz STW oscillator. The 50 to 65dB degradation in phase noise performance as a result of the digital signal processing of the SAWO signal in the integrated PLL circuits is the price that has to be paid for improving the medium-term stability of the SAWO to BAW crystal stability. The reason for this dramatic phase noise degradation in the PLL system is the fact that the SAWO signal passes through a large number of active devices on its way through the PLL circuit and each of them adds to the overall phase noise [7].

B. Frequency Stabilization and Phase Noise Improvement through injection locking

As explained in [2], the main idea of this work was to provide a SAWO with BAW crystal stability at 1.25V supply voltage without using noisy PLL circuits and sophisticated tuning. This idea is based on Adler´s work from 1946 that demonstrated efficient stabilization of the frequency of a free running oscillator by means of an external small power signal with nearly the same frequency and high stability injected in the oscillator loop [8]. Adler called this phenomenon injection locking and showed that the free running oscillator can lock onto the injected signal and adopt its medium and long-term stability over an injection locking bandwidth (ILBW) BW_{inj} which depends on the power ratio of the injection versus loop power P_{inj}/P_{loop} in the point of injection as follows:

$$BW_{inj} \propto \frac{F_o}{Q_L} \times \sqrt{\frac{P_{inj}}{P_{loop}}} \qquad (1),$$

where F_o and Q_L are the frequency and loaded Q of the free running oscillator, accordingly. Since in the locked state, the frequencies of injection and free running sources are identical over the entire ILBW, the injection locked oscillator adopts the medium and long-term stability of the injection reference. This is an efficient way of stabilizing the frequency of a high-frequency LC-type or strip-line power oscillator by injection locking it to a low-power high harmonic of a crystal oscillator which provides crystal stability over temperature, supply voltage and load variations while the system retains the high power of the free running oscillator.

Later on, the injection locking phenomenon was also applied to and studied in SAW oscillators [9, 10] and it was shown that an injection locked SAW oscillator (ILSO) can track possible phase and frequency modulation of the

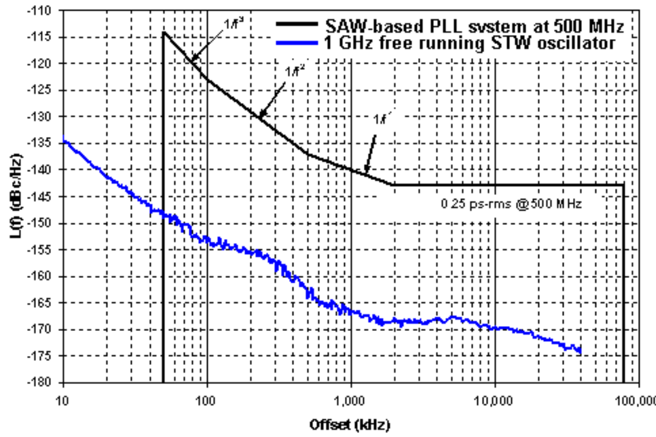
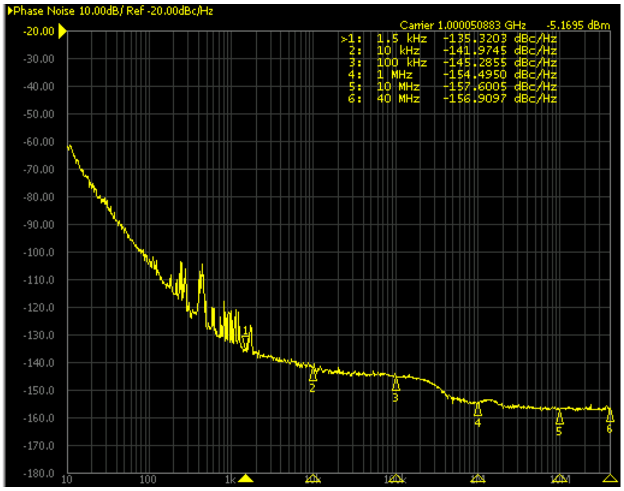


Fig. 1. Phase noise performance of a 500 MHz SAW-based PLL system versus a free running 1 GHz STW oscillator

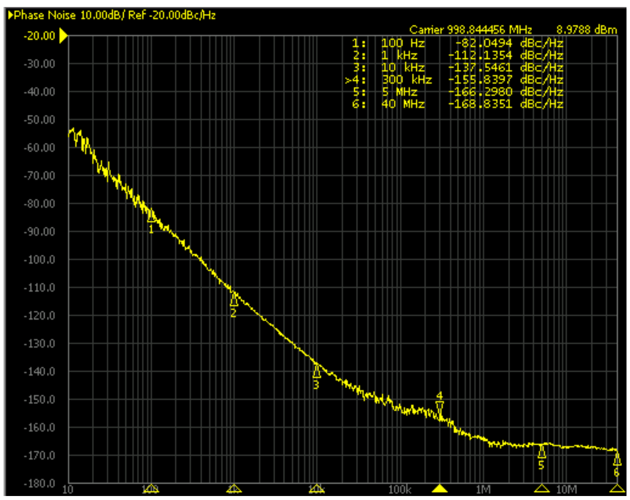
injection signal over a fairly small Q-dependant modulation bandwidth (typically a few kHz [10]). However, due to energy storage effects in the acoustic device, the ILSO cannot track higher frequencies modulating the reference source meaning that above a few kHz away from carrier, it retains its own phase or frequency modulation. These investigations generated the idea that it should be possible to build an ILSO with phase noise performance which is a combination of the lower close-in phase noise of BAW crystal oscillators and the much better thermal noise floor of a free running SAW oscillator.

Fig. 2 a) and b) compares the phase noise data of the 100MHz crystal controlled comb spectrum oscillator (CCCSO) from [11] at its 10-th overtone (1GHz) with a 1GHz free running SAW oscillator stabilized with a two-port STW resonator. Both oscillators operate on 1.25V supply voltage and generate -6 and 9dBm of output power at 1GHz, accordingly. Even at its 10-th overtone, the CCCSO provides 23dB lower close-in phase noise than the free running SAW oscillator which is attributed to the much higher crystal Q at 100MHz. This is evident by comparing the phase noise data at 100Hz and 1kHz offset frequencies. At large carrier offsets (5MHz and higher) where the thermal noise floor occurs, the SAW oscillator provides about 13dB better phase noise than the 10-th crystal overtone which is attributed to the much higher loop power of the SAW oscillator.

Ideally, a phase noise combination of both oscillators in an injection locked system would look like the data in Fig. 3 in which the expected phase noise is given by the thick white solid line. Up to about 1kHz carrier offset, the ILSO adopts the close-in phase noise of the injection source which is by about 20dB lower than in the free running SAW oscillator. In the transition offset frequency range from 1kHz to 1MHz, the phase noise is an average between the phase noise of injection and free running sources and in the thermal noise floor area above 1MHz, the noise performance is governed entirely by the SAW oscillator due to its high output power. In that noise floor offset range, the ILSO cannot track the noise modulation of the injection source and in fact it serves as a noise clean-up filter and parametric amplifier for the injection source signal [12].



a)



b)

Fig. 2. Phase noise of (a) the 10-th overtone of a 100 MHz crystal oscillator at 1GHz and (b) a free running 1GHz STW oscillator.

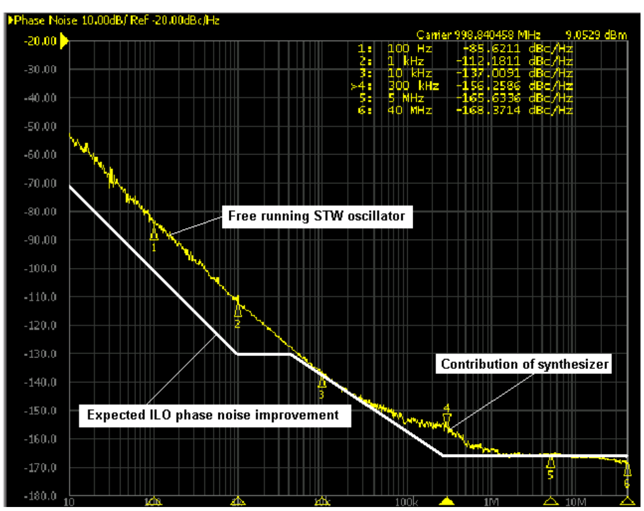


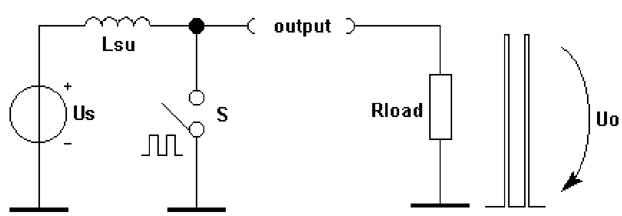
Fig. 3. Expected phase noise improvement of an ILSO compared with the noise performance of a free running SAW oscillator at 1GHz.

C. Low-voltage operation

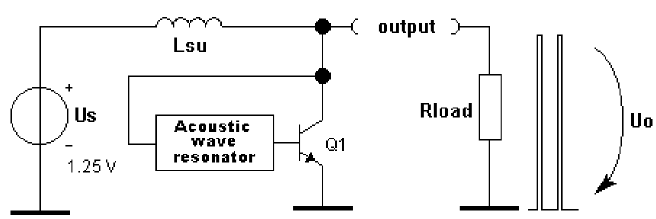
One of the most important features of the proposed ILSO system is that it provides high output power as required for low thermal noise floor of the output signal. The key to achieving high-power operation at 1.25V supply voltage is the implementation of the nonlinear "step-up" converter method widely used in highly efficient DC-DC converters to transform a low-voltage DC source to a high-voltage DC source with low internal resistance at minimum loss of energy [3]. This is done by converting the low-voltage DC source into a pulse stream whose amplitude is up-transformed to a value that is much higher than the voltage of the supplying DC source. Then, the high-voltage pulses are detected by a diode, ripples are filtered out by a shunt capacitor and the output is a DC source with a voltage practically up to 5 times higher than the original one.

The same idea was implemented also to the oscillators used in the ILSO system in order to achieve high-power operation at 1.25V supply voltage. The simplified schematic of the step-up converter and its practical implementation in an acoustic wave oscillator are shown in Fig. 4 a) and b) accordingly. The low-voltage DC source *Us* is "chopped" into pulses by the switch S in Fig. 4 a) which is operated by an external pulse stream. When this switch is on current flows from the DC source to ground charging the storage inductor *Lsu*. When the inductor is fully charged, the switch goes off, the voltage across *Lsu* reverses polarity and adds to the voltage of the DC source. As a result of that, the pulse amplitude *Uo* across the load resistor *Rload* is higher than *Us* and its actual value depends on the duty ratio D of the pulse stream operating the switch.

The system from Fig. 4 a) can easily be made self oscillating by replacing the switch S with the sustaining amplifier transistor Q1 of a BAW crystal or SAW resonator based oscillator as shown in Fig. 4 b). The output of such an oscillator is a stream of narrow high-power pulses across the load resistor (typically 50Ω) whose amplitude is much higher than the 1.25V voltage provided by the DC source. In addition,



a)



b)

Fig. 4. Simplified schematics of (a) the step-up converter and (b) its practical implementation in an acoustic wave based oscillator.

these pulses are rich in harmonics and practically represent a comb spectrum in the frequency domain [11]. In this system, the signal used for injection locking is the spectral line corresponding to the 10-th overtone of the 100MHz CCCSO realized as a crystal reference source according to the schematic from Fig. 4 b) (see also Fig. 2 b) in [11]).

The free running 1GHz STW oscillator (STWO) in the system is also realized according to the step-up converter principle but the acoustic wave resonator in Fig 4 b) is a two-port STW resonator device with a loaded Q of about 3000 and an insertion loss of about 5 dB. Design details on this oscillator are given in [5]. Within this study, we built prototypes of such 1.25V oscillators with up to 12dBm of output power and 25% RF/DC efficiency at 1GHz.

D. The Injection Locked Surface Wave Oscillators (ILSO)

The block diagram of the ILSO is shown in Fig. 5. The storage inductors *Lsu1* and *Lsu2* and sustaining transistors T1 and T2 perform the step-up converter function for the 100MHz CCCSO used as a reference and for the free running STWO used for high-power output, accordingly. To provide maximum power ratio and maximize the ILBW according to (1), the 1GHz injection locking spectral line is extracted through a matching network from the CCCSO spectrum and fed through an injection coupler to the point of minimum loop power in the STWO. In this ILSO, two identical two-port STW resonators are used - STWR1 for stabilizing the frequency of the STWO and STWR2 used as a cleanup filter for removing unwanted CCCSO harmonic residues from the output spectrum. The voltage controlled variable phase shifter (VPS) provides ±3 to ±6ppm electronic tuning of the CCCSO frequency on both sides of the 1000.000 MHz goal frequency to allow its precise adjustment at room temperature [11]. Reference [11] provides further design details on the system.

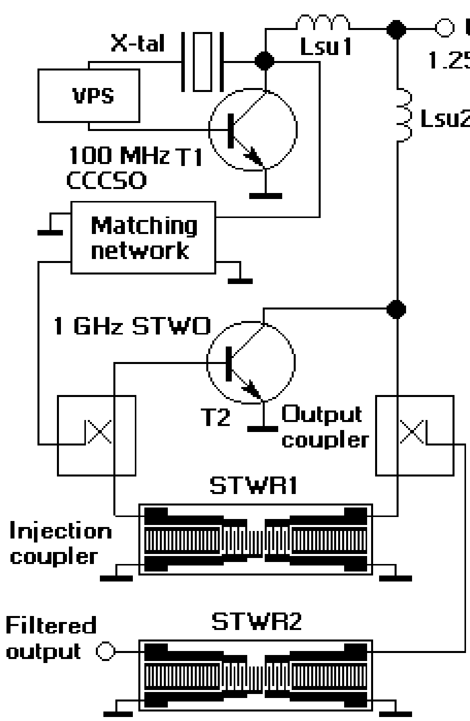


Fig. 5. Block diagram of the ILSO.

TABLE 1. ILSO PARAMETERS

ILSO version	High power	Low power
ILSO frequency at 25°C	1000.000MHz	1000.000MHz
Supply voltage	1.25V	1.25V
Supply current	90mA	53mA
Output power	4dBm	-4dBm
Pull range	±3ppm	±6ppm
Injection locking bandwidth	90ppm	240ppm
Locking temperature range	(0 to 70)°C	(-20 to 85)°C
CCCSO harmonic suppression	>55dB	>60dB

Two versions of the ILSO were designed, built and tested. Their parameters are listed in Table 1. The high-power version was designed with a weak coupling of the injection signal to the STWO loop to keep the output power and the thermal noise floor to a maximum. Its purpose was to verify the expected phase noise performance from Fig. 3 regardless of the locking bandwidth. This version had about 90ppm ILBW and was found to maintain lock over a fairly narrow temperature range from 0 to 70°C.

The low-power version was designed to maintain lock over a much larger temperature range (design goal was (-40 to 85)°C). The 240ppm ILBW necessary for covering this temperature range (see Fig.6 below) was achieved by making the injection coupling stronger and by lowering the STWO loop power as required by (1). The lower temperature edge of -40°C for this ILSO could not quite be reached since the turn-over temperature of the STW device in the STW was by about 15K higher than required for the 200ppm temperature induced frequency shift over the above temperature range. As a result of that, the ILSO maintained safe lock at up to about 100°C on the high end but lost lock at about -20°C. This problem can readily be solved by a slight correction of the quartz cut orientation of the STW device in the STWO.

III. ILSO PERFORMANCE VERIFICATION

A. Temperature Stability and Phase Noise Improvement

The fact that the ILSO indeed adopts the stability of the BAW crystal controlled injection reference is evident from the comparison of the temperature stabilities of the free running STWO versus low-power ILSO in Fig. 6. A temperature stability improvement by a factor of 16 over the (-20 to 85)°C range is achieved. Also the slight cubic behavior of the ILSO temperature dependence is attributed to the AT-cut behavior of the 100MHz BAW crystal indicating that it governs the temperature behavior of the system.

The phase noise behavior of the high-power ILSO in Fig. 7 is also in a good agreement with the expected performance in Fig. 3. In the close-in offset range below 1kHz the ILSO phase noise performance is entirely governed by the high Q of the

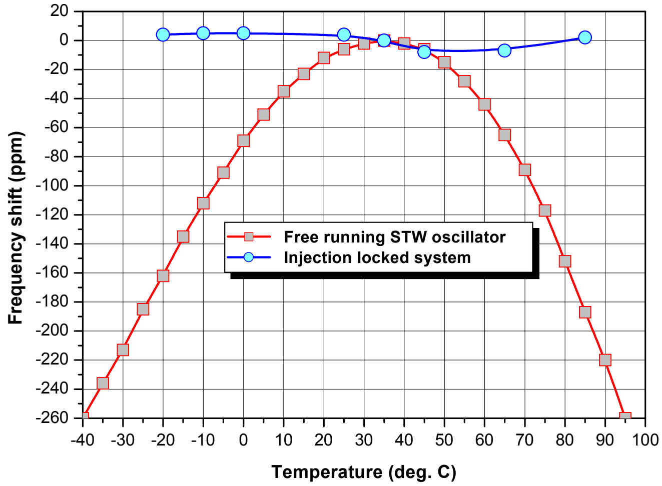


Fig. 6. Temperature stability comparison of the free running STWO vs. low-power ILSO.

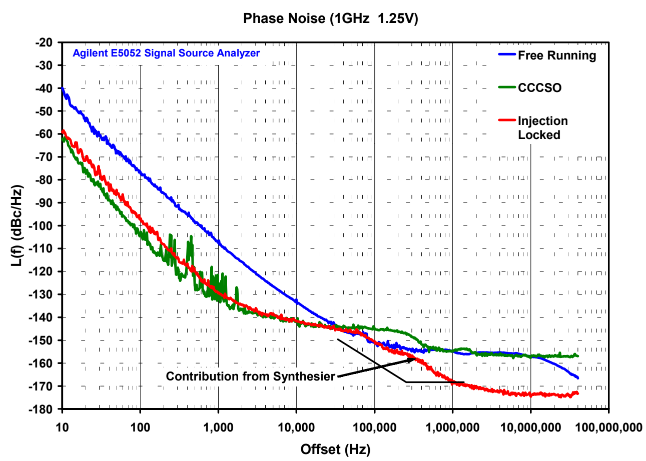


Fig. 7. Phase noise data of the ILSO vs. free running STWO and the 10-th CCCSO overtone used as injection source.

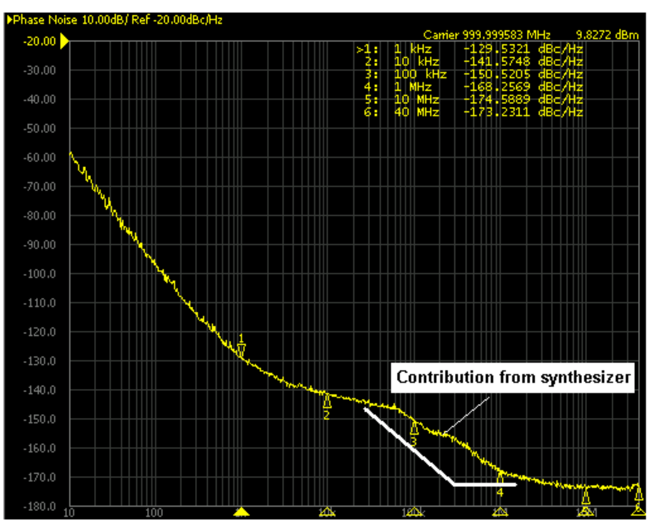


Fig. 8. Detailed phase noise performance of the high-power ILSO.

BAW crystal which results in 18 to 25 dB improvement compared to the free running STWO. In the thermal noise floor offset range above 1MHz the STWO clearly takes over due to its high loop power. In the transition offset range between 1KHz and 1MHz the ILSO phase noise is somewhere between the CCCSO and STWO but still lower than in the STWO.

The final result is shown in Fig. 8 which is the detailed phase noise of the high-power ILSO version. It indicates a noise floor of -174dBc/Hz which, to the best of the author's knowledge, is the lowest noise floor achieved with a low-voltage SAW oscillator so far. The -130dBc/Hz noise suppression at 1kHz carrier offset is consistent with the noise performance of the best multiplied by a factor of ten 100MHz crystal oscillators reported to date [13]. We found that the phase noise bump in Fig. 7 and 8 is attributed to the synthesizer of the Agilent E5052 signal source analyzer and is in fact much lower than on the data plot. This was verified by phase noise measurements with an older measurement system.

B. Sensitivity to temperature and supply voltage variations

In a feasibility study laboratory prototypes of low-power ILSO version were systematically tested for their sensitivity towards temperature and supply voltage variations. The goal of these tests was to check suitability for commercial products.

The data plots in Fig. 9 represent sensitivity of the ILSO output power to ±10% supply voltage variations over temperature. In this experiment the ILSO output was connected to an amplifier with 12dB of gain to isolate the ILSO from possible load variations and the output power was measured at 8 different temperatures in the (-30 to 85)°C range. The supply voltage was varied between 1.08 and 1.35V. Since the system lost lock slightly below -20°C, only the upper 7 curves represent the actual ILSO power behavior of the ILSO. The lowest pink curve is the power variation of the CCCSO injection signal in the unlocked state at -30°C. All 8 curves indicate a power variation in the ±1.5 to ±2.5dB range when the supply voltage is varied by ±10% at all 8 temperatures. This is valid for the ILSO (upper 7 curves) and for the 10-th overtone of the CCCSO (lowest pink curve). The ILSO power variation over temperature is in the 7 to 8 dB range which is fairly high.

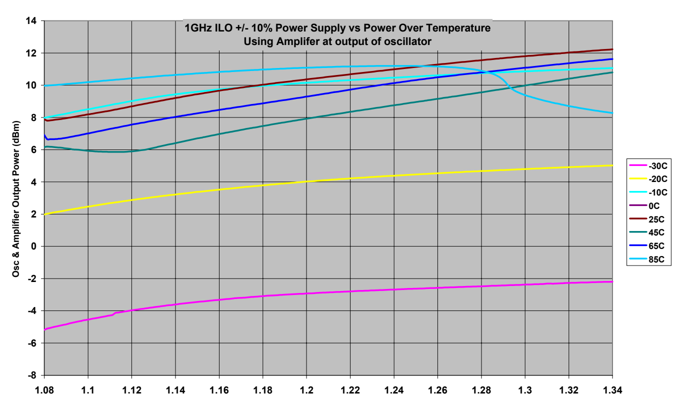


Fig. 9. ILSO and CCCSO output power sensitivity with temperature and supply voltage variations.

We attribute this behavior to the absence of negative current and voltage feedback in the CCCSO and STWO circuits which degrades the thermal stability of the collector current in the sustaining amplifier transistors. Keeping in mind that Si bipolar transistors need at least 0.7V collector emitter voltage in the conducting state, the voltage margin of about 0.55V is all we have available for proper switched operation of the sustaining transistors as required for the step-up conversion function. Because of that, we did not use negative feedback which results in a fairly poor thermal collector current stabilization and relatively high output power variation over temperature. In our opinion, a compressed amplifier at the ILSO output could reduce the output power fluctuations over temperature at the expense of some noise floor degradation.

The data plots in Fig. 10 represent the ILSO frequency sensitivity to supply voltage variations over temperature which is governed by the CCCSO stability in the locked state. When the supply voltage is varied by ±10% the ILSO frequency varies by ±7ppm. For a crystal controlled oscillator this sensitivity is considered fairly high and we attribute it again to the absence of negative feedback in the sustaining amplifier. We believe that a low-dropout-voltage regulator stabilizing the supply voltage at 1.2V could greatly reduce the ILSO sensitivity to supply voltage variations. On the other hand, the ILSO temperature stability is within 12ppm over the entire (-20 to 85)°C operating range which is an excellent stability for a crystal controlled oscillator.

Figure 11 represents the phase noise sensitivity of the high-power ILSO version in the temperature range (25 to 85)°C. Up to 500kHz offset frequency the phase noise variation does not exceed 7dB. In the thermal noise floor range above 1MHz the phase noise variation is about 13dB. This is again attributed to output power variations as a result of thermal collector current stabilization.

The phase noise variation over temperature of the low-power ILSO version is somewhat stronger pronounced than in the high power version. This is evident from Fig. 12 and is attributed to the fact that the low-power version is operated over a much larger temperature range. The curves measured

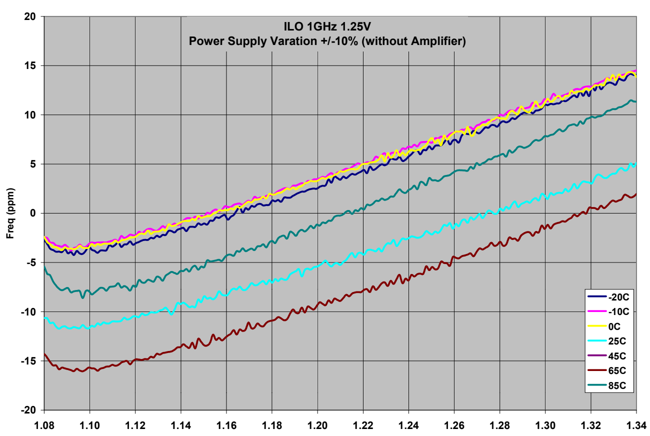


Fig. 10. ILSO frequency sensitivity to supply voltage variations over temperature.

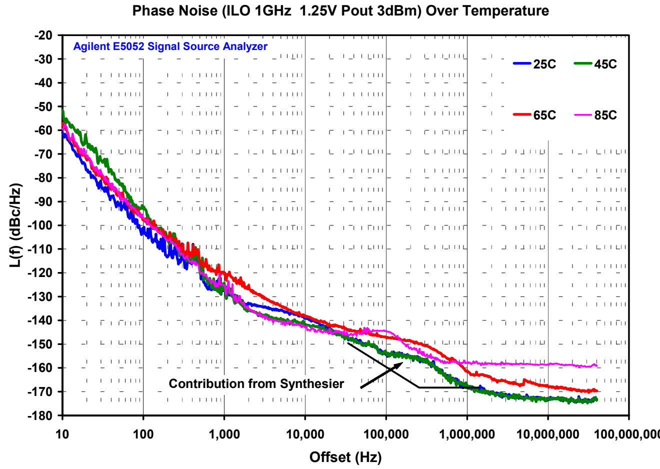


Fig. 11. Phase noise of the high-power ILSO over temperature.

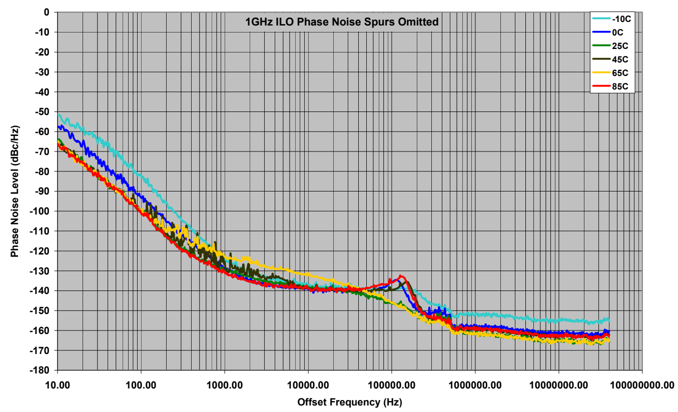
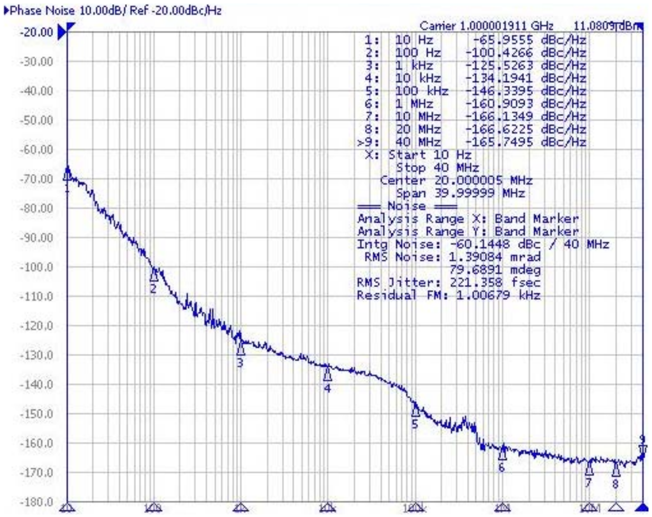


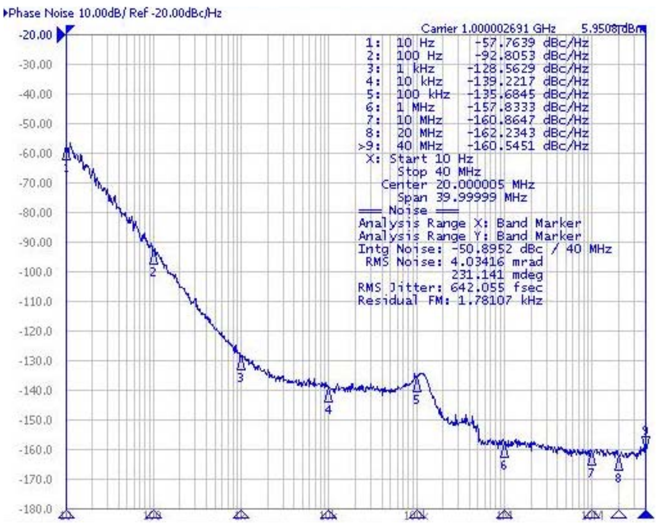
Fig. 12. Phase noise of the low-power ILSO over temperature.

at the lower and upper edges of the temperature range show a bump at about 150kHz offset frequency indicating that the ILSO approaches the lower and upper edges of the ILBW where it is about to lose lock.

Finally, Fig. 13 a) and b) contain the integrated r.m.s. jitter performance of one of the low-power ILSO prototypes for operation at 85°C, i.e. closer to the ILBW center and still far from the upper ILBW edge, and at 0°C where the ILSO approached the lower ILBW edge and was bound to loose lock. With this ILSO prototype, we were unable to adjust the center of the ILBW at room temperature since the turn-over point of the STW device that we had available for the free running STWO was by about 25K higher than desired. As a result of that, at 85°C the ILSO was operating in a more stable region than at 0°C. At these two temperatures the integrated r.m.s. jitter is 220 and 640 fs, accordingly, as derived from the phase noise data. Despite the fact that jitter numbers vary by a factor of 3 over the operating temperature range, they stay in the fs range. To the best of the authors' knowledge, this is the best jitter performance reported with a low-voltage SAW oscillator to date. We believe that jitter variation over temperature could be significantly reduced if Rayleigh SAW devices with better temperature stability are used in the system.



a)



b)

Fig. 13. Integrated r.m.s. jitter performance of one of the the low-power ILSO prototypes at (a) 85°C and (b) 0°C.

IV. Summary and Conclusions

This experimental study has verified the predicted by Adler's theory and expected performance of STW based injection locked oscillators stabilized with a spectral line of a crystal controlled comb spectrum oscillator injected in the loop of a free running high-power STW oscillator. The 1GHz ILSO prototypes operate on an extremely low 1.25V supply voltage, generate up to 4dBm of output power and provide a thermal noise floor of -174dBc/Hz. Lower power versions maintain safe lock over the (-20 to 85)°C range and provide integrated r.m.s. jitter performance in the fs range. Compared to a free running STW oscillator, temperature stability improvement by a factor of 16 and close-in phase noise reduction by 18 to 25dB as a result of BAW crystal stabilizati-

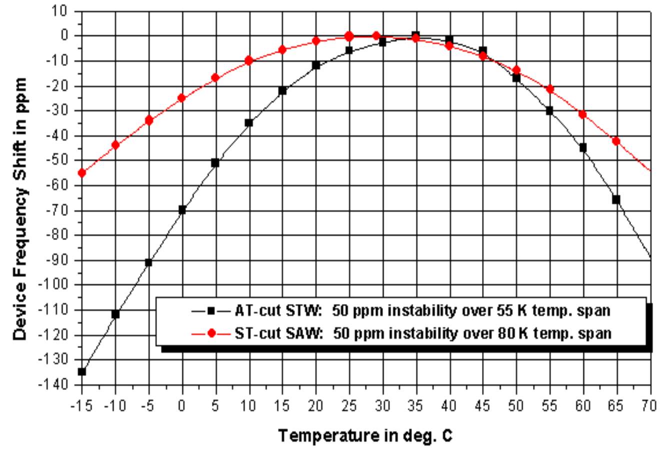


Fig. 14. Temperature stability of Rayleigh SAW versus STW devices on temperature compensated rotated Y-cut orientations of quartz.

on has been demonstrated.

Despite the remarkable phase noise and jitter performance, as well as excellent thermal stability achieved at very low supply voltages the proposed ILSO system requires careful adjustment of the turn-over temperature and tight fabrication tolerances of the SAW device to maintain lock over the desired temperature range. In addition, it demonstrates a fairly high sensitivity of the output power over temperature which is attributed to the absence of negative feedback for collector current stabilization. The necessity of using large ILBW can be eased by using a Rayleigh SAW devices in the free running SAW oscillator. As evident from Fig. 14, Rayleigh SAW devices feature about 2.5 times lower temperature sensitivity than their STW counterparts which greatly enhances the requirement for using large injection locking bandwidths. The frequency and power sensitivity to supply voltage and temperature variations can be reduced by using low-dropout voltage regulators for the supply voltage and using compressed amplifiers at the system output.

It is the authors' belief that in the near future, ILSO systems may become a competitive alternative to noisy PLL systems in applications requiring low-voltage operation.

References

[1] I. D. Avramov, "Very Wide Tuning Range, Low-Noise Voltage Controlled Oscillators Using Ladder Type Leaky Surface Acoustic Wave Filters", *Proc. 1998 IEEE International Frequency Control Symposium*, pp. 489-496.

[2] I. D. Avramov, "Low-voltage, high performance STW clocks with BAW crystal stability", *Proc. 2005 Joint IEEE Int. Freq. Control Symp. and Precise Time&Time Interval (PTTI) Systems&Applications Meeting, pp.* 880-885.

[3] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converter, Applications and Design.* New York: Wiley, 1989.

[4] I. D. Avramov, "Phase Noise Reduction in Surface Wave Oscillators by Using Nonlinear Sustaining Amplifiers", *Proc. 2003 IEEE International Frequency Control Symposium and DA Exhibition Jointly with the 17th European Frequency and Time Forum*, pp. 478-486.

[5] I. D. Avramov, "Low Voltage Surface Transverse Wave Oscillators for the Next Generation CMOS Technology", *IEEE Transactions on*

Ultrasonics, Ferroelectrics and Frequency Control, vol. 52, No. 8, Aug. 2005, pp 1247-1252.

[6] I. D. Avramov, "Phase noise performance of low-voltage STW based voltage controlled oscillators in the 0.9 to 2.4 GHz frequency range, *Proc. 2005 Joint IEEE Int. Freq. Control Symp. and Precise Time&Time Interval (PTTI) Systems&Applications Meeting,* pp. 872-879.

[7] T. E. Parker and G. K. Montress, "Precision surface-acoustic-wave (SAW) oscillators", *IEEE Trans. Ultrason. Ferrolelectrics and Freq. Control*, Vol. 35, No. 3, May 1988, pp. 342-364.

[8] R. Adler, "A study of locking phenomena in oscillators", in *Proc. IRE,* vol. 34., No. 6, pp. 351-357, June 1946.

[9] C. K. Campbell, "FM demodulation at UFH frequencies using an injection locked SAW oscillator", *Trans. Sonics Ultrason*., vol. (SU 29), no. 6, pp. 310-316, Nov. 1982.

[10] I. D. Avramov, P. J. Edmonson and P. M. Smith, "A surface transverse wave-based MSK system", *IEEE Trans. Ultrason. Ferrolelectrics and Freq. Control*, vol. 38, no. 3, May 1991, pp. 194-198.

[11] I. D. Avramov, "Low-voltage crystal controlled comb spectrum oscillator for injection locked STW based clocks with improved stability", *Proc. 2006 IEEE International Frequency Control Symposium*, pp. 393-400.

[12] I. D. Avramov, "Microwave oscillators stabilized with surface transverse wave resonant devices", *Proc. 1992 IEEE International Frequency Control Symposium,* pp. 391-408

[13] D. V. Bogomolov, E. A. Silaev, "Nonlinear dependencies and phase noise in precision crystal oscillator", in *Proc. 2000 IEEE/EIA Int. Freq. Cont. Symp. and Exp*., pp. 549-552.