TCMO™: A VERSATILE MEMS OSCILLATOR TIMING PLATFORM

K. J. Schoepf
Sand 9, Inc.
8 St. Mary's St. 628, Boston, MA 02215, USA
E-mail: ***jschoepf@sand9.com***
R. Rebel, D. M. Chen, G. Zolfagharkhani, A. Gaidarzhy,
J. H. Kuypers, M. Crowley, and P. Mohanty
Sand 9, Inc.

Abstract

This paper demonstrates the first MEMS oscillator with a performance comparable to a temperature-compensated crystal oscillator (TCXO) in frequency accuracy, temperature stability, and phase noise. The presented temperature-compensated MEMS oscillator (TCMO™) achieves –116 dBc/Hz phase noise at 1 kHz offset from the 123.9 MHz carrier, relating to a phase noise value of −135.6 dBc/Hz at 1 kHz offset at 13 MHz. The temperature drift of the MEMS oscillator is within ±2.5 ppm over the entire operating temperature range from –40°C to +85°C. The TCMO™ uses a unique circuit architecture for an analog temperature compensation so that the output frequency does not suffer from frequency or phase discontinuities.

INTRODUCTION

Crystal oscillators (XO) are ubiquitous and irreplaceable components in electronic equipment that require a precise reference frequency. The application of crystal oscillators ranges from clock generation for digital circuits to providing reference frequencies for wireless and wireline communications, entertainment electronics, aerospace, timing applications, military systems, etc. Crystal oscillators are comprised of a quartz crystal resonator with a high quality factor as the resonating element and integrated circuitry (IC) as the oscillator feedback loop. The dominance of quartz crystals as the resonating element in the oscillator remains unchallenged since the discovery of the temperature stable AT and BT cuts in 1934. Crystal oscillators using additional active temperature compensation, also referred to as temperature-compensated crystal oscillators (TCXO), are able to achieve typical frequency stabilities of ±2.5 ppm or better over the entire operating temperature range from –40°C to +85°C, aging of below ±1 ppm/year (at 25 °C), typical phase noise of –138 dBc/Hz at 1 kHz, and power consumption as low as 1.5 mA. The smallest commercially available TCXOs are currently available with dimensions of 2.0 × 1.6 × 0.8 mm.

Despite quartz being the material of choice for high-performance TCXOs, there are several drawbacks and limitations to this technology. The first difficulty is related to the attachment of miniaturized quartz plates to the ceramic package with solder balls. Precise control during the assembly is crucial to prevent spurious modes as well as packaging-related stresses from affecting the temperature stability of the quartz resonator. Second, quartz is a fragile material. The pressure of handset manufacturers moving towards smaller packages has led to the use of smaller quartz plates and, as a consequence, thinner plates to prevent the deterioration of the resonator performance. As the resonance frequency of the quartz plate is determined by the thickness of the quartz plate and the mode being used, the absolute manufacturing tolerances become more challenging for thinner plates. For example, handset manufacturers must now specify an allowable frequency shift for smaller TCXOs in the solder reflow process whereby the TCXO is mounted on a circuit board, because the reflow process impacts the solder balls that attach the quartz crystal to the ceramic package. It should be noted that, although the basics of the quartz oscillator technology pioneered by Pierce in 1923 have not changed, there have been many technical advances in recent years to address the issue of miniaturization **[1][2]**.

With the advent of microelectromechanical systems (MEMS) technology, there has been an ongoing debate whether MEMS resonators could offer a competitive alternative to quartz crystal resonators. In particular, as the integration difficulties of the quartz crystal with the oscillator IC scale inversely with the size of the package, the use of MEMS resonators would promote a monolithic solution of MEMS and IC. Commercial MEMS oscillator solutions targeting low-end timing solutions are now available from SiTime **[3]** and Discera **[4]**. As presented by Discera's CTO W. T. Hsu at last year's PTTI Meeting **[5]**, MEMS oscillators to date have failed to achieve the combination of: (1) temperature stability, (2) low phase noise, and (3) frequency accuracy, as required for a TCXO alternative. In this paper, for the first time, we demonstrate that a MEMS oscillator developed at Sand 9 referred to as temperature-compensated MEMS oscillator (TCMO™) meets these three requirements.

MEMS OSCILLATOR DESIGN

The feasibility of batch fabrication in MEMS processing is very powerful in terms of cost leverage of the resonator part of the oscillator. However, it is impossible to manufacture a MEMS resonator to the required accuracy of the initial frequency of typical ±1.5 ppm. This accuracy range is also well beyond the capabilities of available tools and techniques for trimming. At the same time, MEMS resonators made of typical MEMS materials, including silicon, will generally have first-order temperature coefficients of frequency (TCF) in the range of −20 ppm/K to −30 ppm/K. If uncompensated in the oscillator circuit, this large TCF will cause frequency excursions of several thousand ppm over the temperature operating range, far beyond the acceptable ±2.5 ppm for a typical TCXO. In order to account for both fabrication tolerances during production as well as the inherent temperature sensitivity of typical MEMS resonators, commercially available MEMS oscillators have chosen a fractional divider based phase-locked loop design, referred to as Fractional-*N* PLL **[6]**.

Although the fractional-*N* PLL is ideal for adjusting the initial frequency offset with the combination of a temperature sensor read-out and related look-up table dynamically adjusting for temperature variations, it has the inherent disadvantages of large phase noise, strong jitter, frequency jumps/discontinuities, high power consumption, and strong spurious content in the oscillator output **[5][6]**. This approach can be successful for low-end timing solutions where the oscillator performance and power consumption are not critical, and low-cost, high flexibility with customer specific frequencies, short lead time, and added ruggedness due to the MEMS resonator are the determining factors.

Our approach to the development of a high-performance MEMS frequency reference, presented here for the first time, is very different. Initially, we evaluated different oscillator architectures in combination with different MEMS resonator structures that would support low phase noise, low power consumption, and temperature stability, comparable to TCXOs. We designed the MEMS oscillator from the system's level utilizing a different type of MEMS resonator design, along with a novel circuit architecture. Many parameters had to be optimized in the system, which resulted in the specifications for both resonator and circuit. We believe this oscillator architecture is suitable to match the performance of state-of-the-art TCXOs. The oscillator architecture is illustrated in the block diagram in Figure 1. The most significant attributes are the tunability of the oscillator frequency, the inherent temperature stability of the resonator, and the proprietary variable-integer PLL developed by Sand 9. The initial frequency of the oscillator is set by a combination of tuning the resonance frequency of the resonator by the circuit, since the correct design of the combination of MEMS and IC is critical. The amount of tuning necessary for our design is much lower than other technologies. Our approach can tolerate significant variance in the initial resonance frequency of the resonator and, therefore, no trimming of the resonator is necessary.

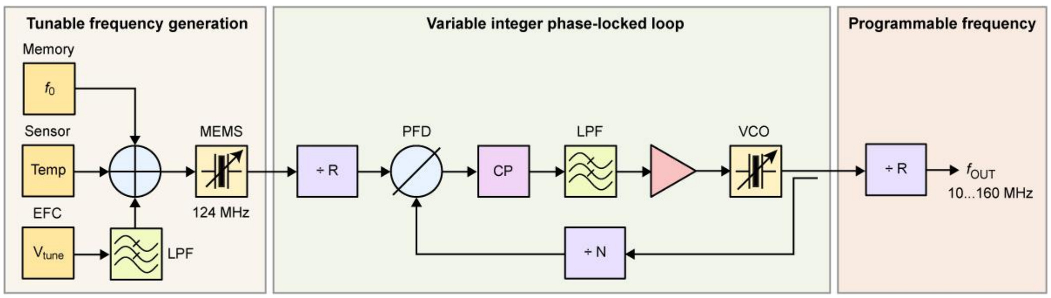


Fig. 1. Block diagram of the temperature-compensated MEMS oscillator (TCMO™) consisting of three functional blocks: tunable frequency generation, variable integer phase-locked loop, and programmable frequency output.

The temperature stability demonstrated by the TCMO™ is comparable to a TCXO. This is achieved in part by using a MEMS resonator that is inherently temperature stable and tunable. The residual temperature drift of the MEMS resonator including manufacturing tolerances is compensated by the circuit to achieve a frequency error below ±2.5 ppm over the entire temperature operating range from −40°C to +85°C.

RESULTS

For the beta generation of the TCMO™ prototype oscillator board, the MEMS resonator is packaged in a standard 6.2 × 4.3 mm LCC ceramic package. This package is commonly used for crystals, and it ensures a hermetic seal of the MEMS resonator and ease of handling during test and assembly. The prototype board of the TCMO™ is shown in Figure 2.

The future fully-integrated TCMO™ product uses wafer-level packaging of the MEMS and IC, resulting in a miniature form factor. It will be available in a chip-scale product (1.5 × 0.8 × 0.5 mm) for direct soldering to the board, flip-chip module assembly or for wire bond connection. The TCMO™ will also be packaged in an SC70-type plastic package that fits common universal footprints for 2016 and 2520 TCXOs, as shown in Figure 3.

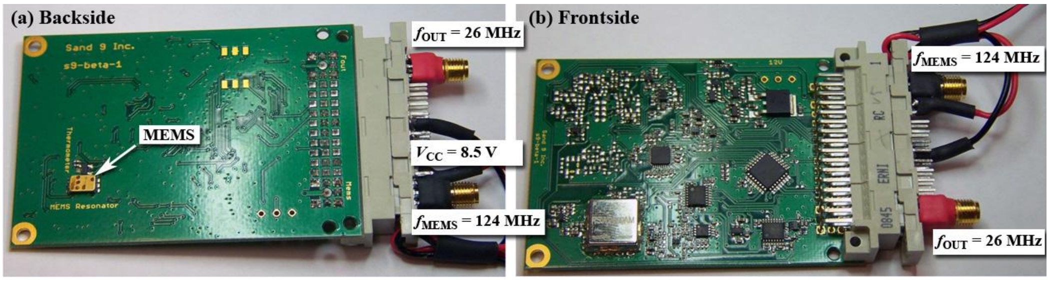
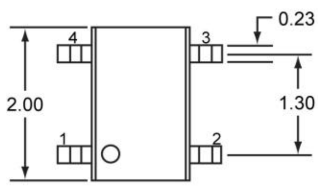


Fig. 2. Image of the beta version of the TCMO™ prototype board that is being transferred to a fully integrated solution. (a) The backside of the circuit board is comprised of the MEMS resonator in a LCC ceramic package and a temperature sensor beside it. The synthesizer and temperature control are implemented on the frontside (b).



Pin Configuration		
Pin#	VC-TCMO	TCMO
1	V_TUNE	GND
2	GND	
3	OUTPUT	
4	VCC	

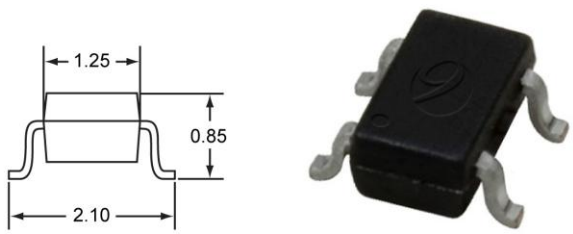


Fig. 3. Illustration of the package for the future fully integrated TCMO™. The package is similar to a 4-pin SC70 and is pin-compatible with the common universal footprints for both 2016 and 2520 TCXOs.

PHASE NOISE

Figure 4 shows the phase noise of the MEMS oscillator. The single sideband (SSB) phase noise of the beta generation of the TCMO™ was measured with an Agilent E5052B signal source analyzer.

In this case, the oscillator output frequency is set by the natural resonance frequency of the MEMS resonator and the initial applied tuning voltage of 4.5 V. The MEMS oscillator achieves a phase noise of −120 dBc/Hz at 1 kHz offset from the 123.9 MHz carrier and a noise floor of −160 dBc/Hz for offsets beyond 100 kHz. Translating the phase noise from the 123.9 MHz carrier to a 13 MHz carrier, using the approximation that the phase noise decreases for the divider factor N as $-20\ \mathrm{Log}_{10}(N)$, yields the second trace in Figure 4. The converted phase noise for the 13 MHz carrier would suggest a noise floor below the noise floor limit of the IC, which has been indicated in Figure 4. Based on this estimate, the phase noise for 13 MHz at 1 kHz offset is −139.5 dBc/Hz.

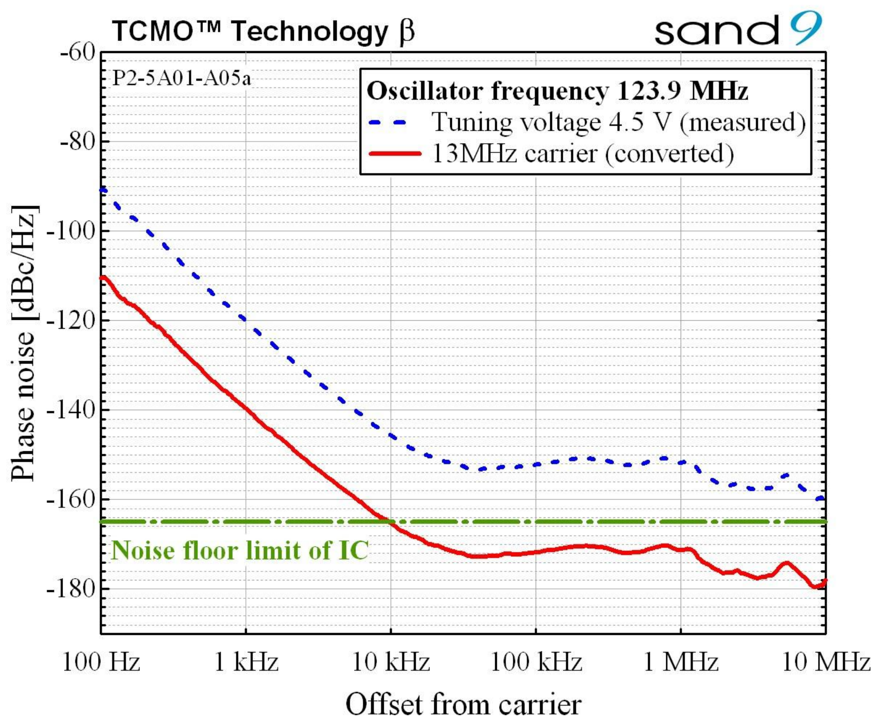


Fig. 4. Measured single sideband phase noise of the 123.9 MHz temperature-compensated MEMS oscillator (TCMO™) and phase noise converted to a 13 MHz carrier.

OSCILLATOR TUNING

The technological key that enables us to achieve an accurate initial frequency of the oscillator and correct for temperature excursions during operation is based on novel tuning and compensation circuit architectures, developed and patented at Sand 9. In general, tuning of the oscillator frequency will always be associated with a degradation of the phase noise. Therefore, a significant design challenge is to minimize the required tuning range in combination with a tuning circuit that causes minimum deterioration of the phase noise. In our case, the coherent choice of the oscillator architecture and the MEMS resonator, combined with a precise integrated design, minimizes the degradation over the required tuning range. The phase noise for different tuning voltages is shown in Figure 5.

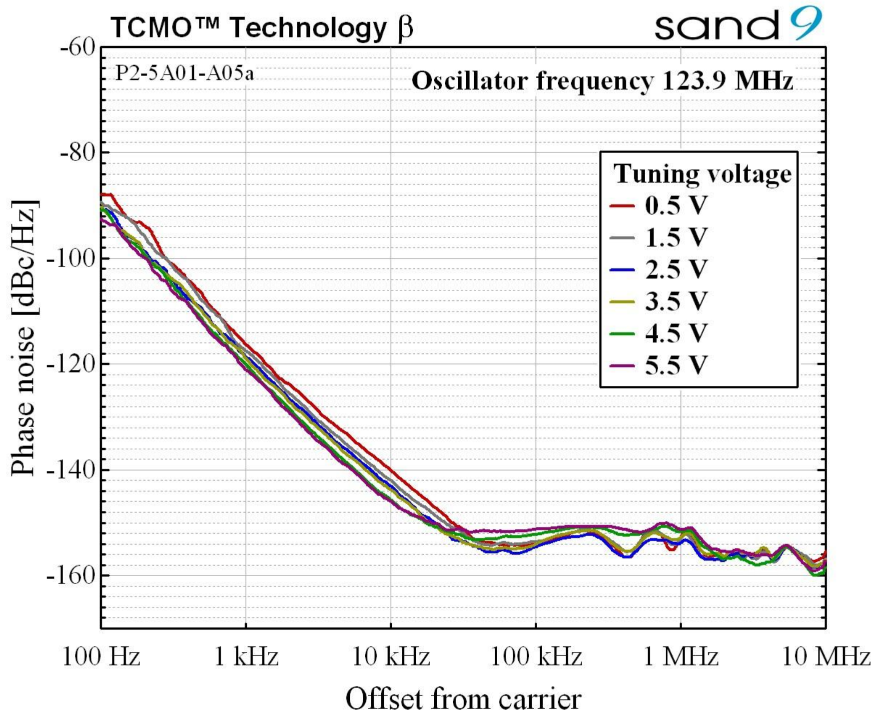


Fig. 5. Tuning voltage dependence of the single sideband phase noise of the 123.9 MHz temperature-compensated MEMS oscillator.

The phase noise characteristics of the TCMO™ are almost unaffected by the tuning. Figure 6 shows the tuning characteristics of the carrier frequency of the oscillator versus the applied tuning voltage along with the phase noise value at 1 kHz. For very large tuning voltages, the phase noise does degrade rapidly, and at 6.7 V, the oscillator becomes unstable and starts to oscillate at a different frequency. The ±200 ppm range indicated in Figure 6 represents the feasible tuning range that does not cause strong degradation of the phase noise of the oscillator or adversely affect the stability. The corresponding voltage range is from 0.6 V to about 6.1 V.

The worst-case phase noise at 1 kHz is therefore −116 dBc/Hz, corresponding to a worst-case degradation of 4.6 dBc/Hz beyond the phase noise at 1 kHz for the ideal tuning voltage of 5 V. The worst-case phase noise for a 10 kHz offset is −139 dBc/Hz. Converting this to a 13 MHz carrier corresponds to −135.6 dBc/Hz at 1 kHz and −158.5 dBc/Hz at 10 kHz. Based on the GSM specifications for a 13 MHz TCXO of −130 dBc/Hz at 1 kHz offset and −150 dBc/Hz at 10 kHz for a 13 MHz reference and the measurement uncertainty of the phase noise measurement with the Agilent E5052B and a generous safety margin, the TCMO™ meets the GSM phase noise requirements.

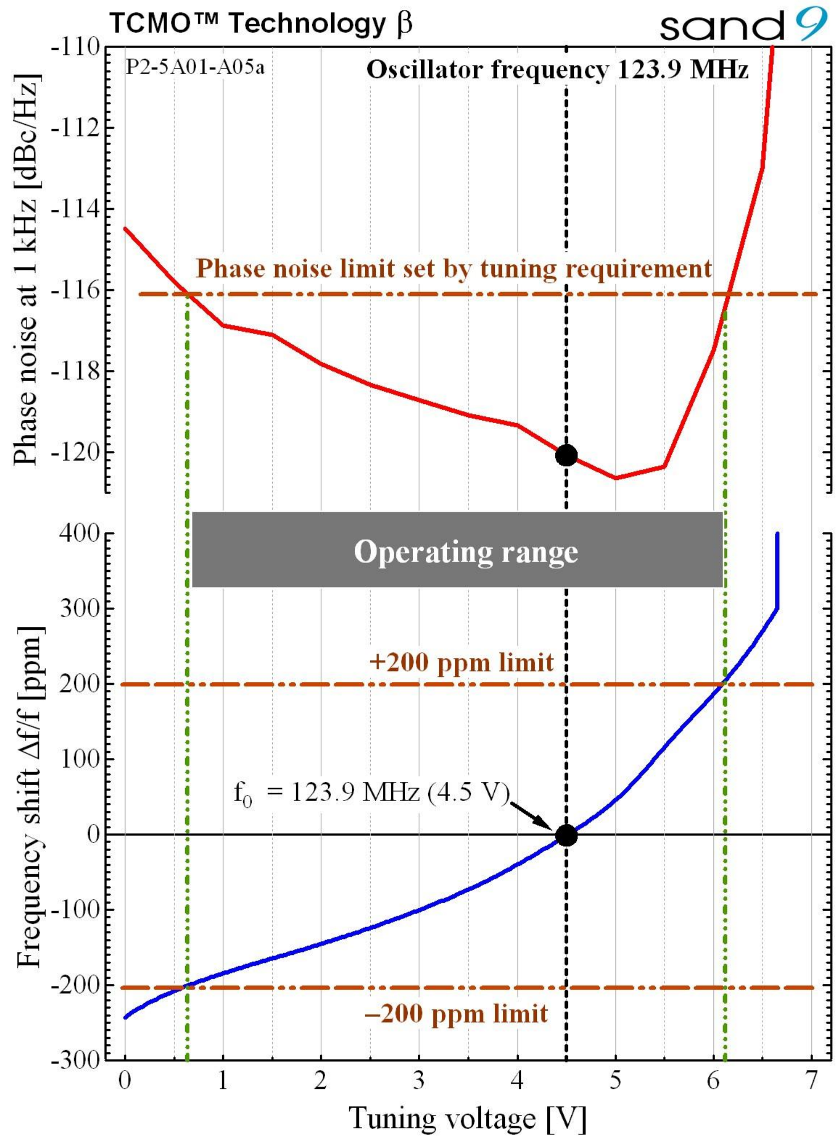


Fig. 6. Result of the frequency tuning of the MEMS oscillator and dependence of the 1 kHz phase noise versus the tuning voltage from 0 to 7 V measured with an Agilent E5052B signal source analyzer.

TEMPERATURE COMPENSATION

In the previous section, we had demonstrated the tunability of our MEMS oscillator. For the beta PCB version of the TCMO™, shown in Figure 2, the temperature compensation is achieved via a temperature sensor (LM60) and a DAC (AD5641) to set the tuning voltage. A microcontroller (ATmega168) does the polynomial calculation to determine the DAC settings. The correct polynomial coefficients are determined during the calibration sequence of the TCMO™. The TCMO™ is then measured over the operating temperature range from –40°C to +85°C. Due to the finite resolution of the ADC (10 bit) and the DAC (14 bit), the temperature compensation is done in small frequency steps. Therefore, the beta PCB shows the same principal behavior as other typical MEMS oscillators when temperature changes.

Due to the weak thermal coupling between the temperature sensor, the MEMS resonator and the oscillator circuit, and self-heating by some of the discrete circuit components, the temperature calibration is difficult and the measurements requires long soak times in a temperature chamber. To avoid the problems of frequency jumps and temperature differences between oscillator and compensation circuit, the integrated TCMO™ will use a pure analog tuning circuit with excellent thermal coupling between the resonator and the oscillator due to the small size and monolithic integration. The frequency stability of the oscillator is shown in Figure 7. It should be noted that the PLL has been programmed to obtain an oscillator output frequency of 26 MHz. The temperature drift of our MEMS oscillator is well within ±2.5 ppm over the entire operating temperature range from –40°C to +85°C, as seen from Figure 7.

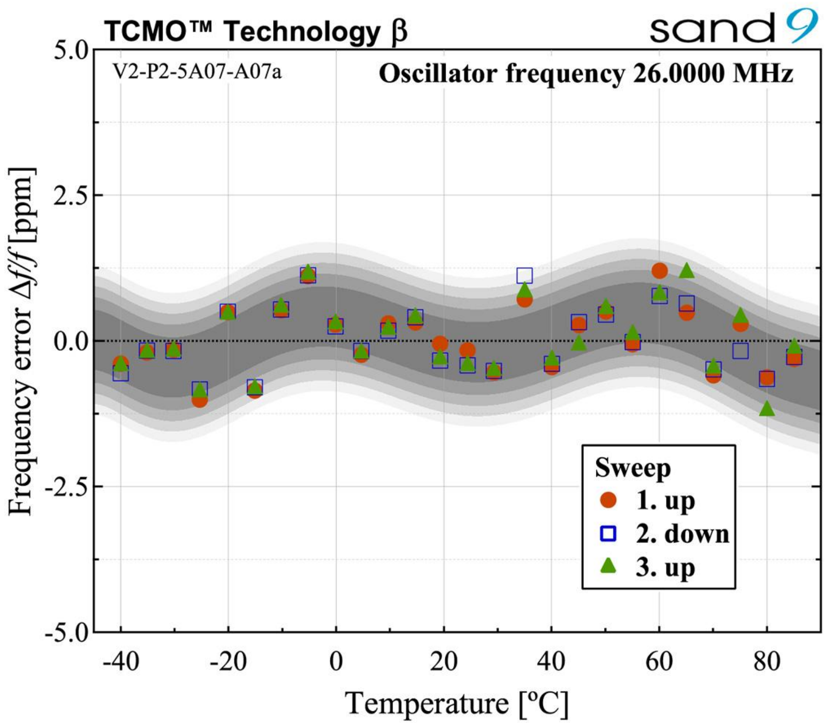


Fig. 7. Frequency error of three consecutive temperature cycles of the TCMO™ over the operating temperature range from –40°C to +85°C.

Time Domain Analysis

The jitter of the MEMS oscillator operating at it its native frequency of 123.6 MHz was evaluated from the single sideband phase noise $L(f)$ measured with an Agilent E5052B signal source analyzer, as shown in Figure 8. The RMS jitter J_{per} is 0.08984 ps at the band from 12 kHz to 20 MHz. The RMS period jitter J_{per} is computed from

$$\text{RMS } J_{per}\Big|_{f_1}^{f_2} = \frac{1}{2\pi f_c}\sqrt{2\int_{f_1}^{f_2} 10^{\frac{L(f)}{10}}\, df}\ . \tag{1}$$

The low jitter value measured for the TCMO™ is promising for a variety of signal processing applications, in particular involving high-speed analog-to-digital conversion requiring high resolution and large dynamic range.

One of the major drawbacks of commercially available MEMS oscillators using a fractional-*N* PLL are the elevated jitter and noise levels originating from the correction of the oscillator frequency by constantly adjusting the PLL divider factors and from the sigma-delta converter. This strongly affects the phase noise within the loop bandwidth of the oscillator. Besides the additional jitter, discrete steps are introduced in the frequency of the oscillator and, hence, in the phase as well. This issue has been treated in the literature **[6]**.

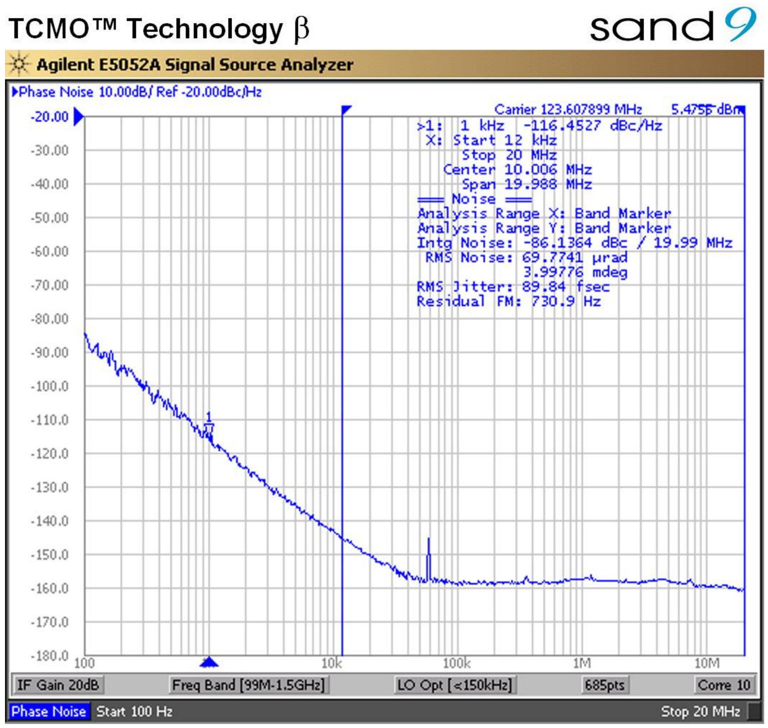


Fig. 8. Evaluation of the RMS period jitter of the MEMS oscillator from the single sideband phase noise measured with an Agilent E5052B signal source analyzer.

SHORT-TERM STABILITY

The frequency data shown in Figure 9 compares the short-term frequency stability of two commercially available MEMS oscillators (Ecliptek EMK43H2H, SiTime SIT80002Al both at 48 MHz), two typical quartz TCXOs (NDK NT22016SA at 26 MHz, Epson Toyocom TG-5025BA at 52 MHz), and Sand 9's TCMO™ (V2-P2-5A07-A07a at 26 MHz). The data were measured at time intervals of 1 s with an Agilent E53131 frequency counter.

The two tested TCXOs (NDK, Epson Toyocom) exhibit very good short-term stability compared to the commercially available MEMS oscillators (Ecliptek, SiTime). The Sand 9 TCMO™ shows good short-term stability similar to the TCXOs. However, it should be noted that the short-term stability of the beta version of the TCMO™ does suffer slightly from jitter originating from the temperature compensation.

As previously mentioned, this jitter is limited by the 10-bit ADC used for the temperature sensor reading in the beta board prototype. The IC that will be used in the fully integrated TCMO™ will use a pure analog scheme and, therefore, will not suffer from the limitations of an ADC or any digital compensation.

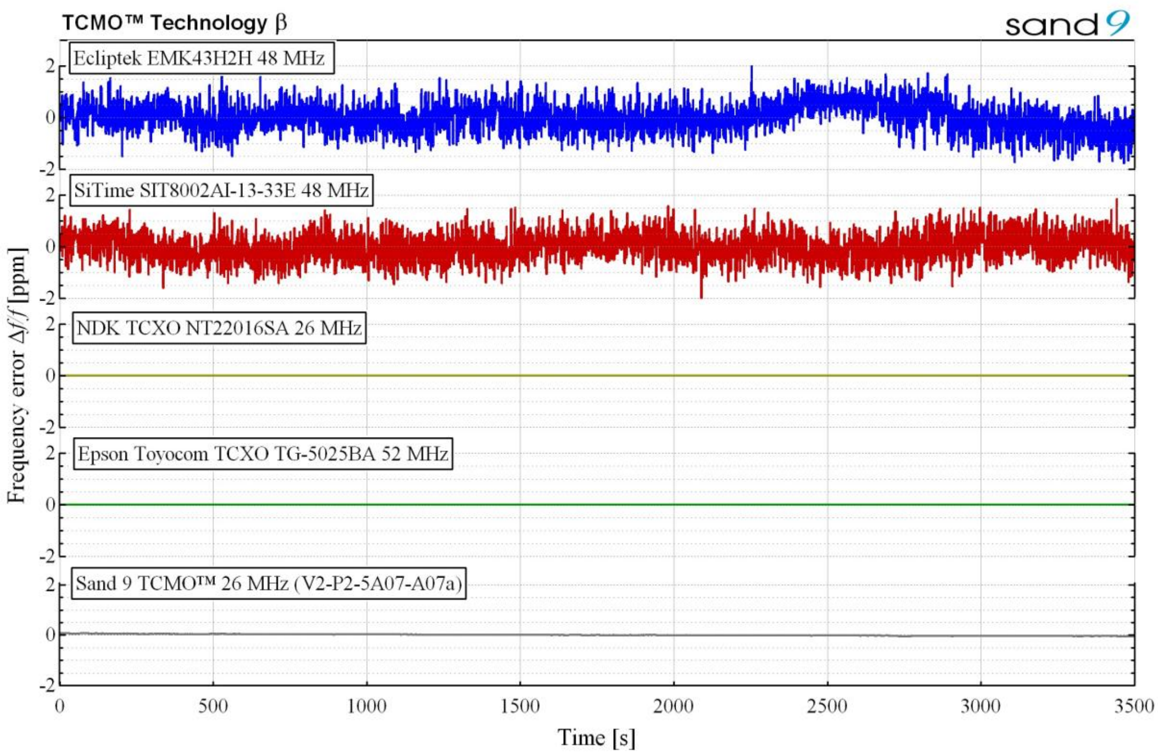


Fig. 9. Comparison of the short-term frequency stability of commercially available MEMS oscillators (Ecliptek, SiTime), quartz TCXOs (NDK, Epson Toyocom), and Sand 9's β-TCMO™. The large jitter observed for the MEMS oscillators originates from the fractional-*N* PLL, whereas the Sand 9 TCMO™ does not show this jitter, although the current beta PCB version does use a digital compensation limited by the 10-bit ADC of the temperature sensor reading. The future IC of the fully integrated TCMO™ will be entirely analog for further improvement.

APPLICATIONS

In the preceding paragraphs, we have addressed the three unmet challenges for MEMS oscillators **[5]**: (1) temperature stability, (2) low phase noise, and (3) frequency accuracy. We have shown that the TCMO™ meets all three requirements. For the first integrated generation, the TCMO™ will offer a programmable output frequency anywhere between 10 MHz and 160 MHz. This frequency configurability will allow for the TCMO™ to have very short lead times with even obscure frequencies in that range. The TCMO™ will use a package similar to an SC70 with 4 pins (see Figure 3) and will be fully pin-compatible with common universal footprints for 2016 and 2520 TCXOs. This package type offers large advantages over traditional ceramic packages in terms of cost and reliability. The TCMO™ will also be available in a chip-scale package with the dimensions 1.5 × 0.8 × 0.5 mm, which is ideal for applications requiring the smallest and thinnest form factor. This miniature package is suitable for multichip module integration and assembly using conventional wire-bond or solder bump techniques. This will be the first generation of MEMS-based oscillators that can be used in applications such as 3G and 4G cellular communications, WiFi, and GPS or other applications where TCXOs are commonly used. The TCMO™ will have many advantages over conventional quartz devices, such as improved mechanical ruggedness and resistance to shock, vibration, and acceleration. It will also be available with an extended temperature range up to 125°C for solutions requiring wider temperature ranges, such as military, automotive, and aerospace applications.

Further enhancements of the fundamental TCMO™ resonator and circuit technology platform should allow a broad resonator product portfolio. The universality of the MEMS resonator manufacturing process will enable products difficult to envision with traditional quartz technology, such as monolithically integrated multi-oscillators, monolithically integrated real-time clock and MHz frequency sources, high-frequency (500MHz-3 GHz) thermally stable frequency sources, and oven-controlled MEMS frequency sources with stability similar to an oven-controlled crystal oscillator (OCXO), but with a significantly smaller form factor and dramatically lower current consumption. The ability to precisely control the resonator manufacturing process by using MEMS process techniques gives the designers unprecedented flexibility. The technology described above can also enable the integration of oscillators and other resonator-based devices, such as filters and gyroscopes, with standard CMOS semiconductors into ultra-high levels of integration.

DISCUSSION

The doubts regarding the maturity of MEMS oscillators raised in several publications **[1][7]** is part of an ongoing debate regarding the claims of the current MEMS oscillator industry of matching the performance of, and hence replacing, crystal oscillators. The basis of this controversy lies mainly in the lack of specifications of what performance metrics a MEMS oscillator has to actually meet in order to replace a crystal oscillator. Although the absolute frequency accuracy, temperature stability, and aging of oscillators are well defined, other performance metrics, such as phase noise, power consumption, jitter, allowable frequency and phase discontinuities, Allan variance, temperature transient recovery time, maximum shock, and vibration sensitivities, are generally not listed in the datasheet of a typical XO, TCXO, or MEMS oscillator. Therefore, it is difficult to directly compare these technologies, as for crystal oscillators a lot of performance metrics, including phase noise and Allan variance, although unpublished in the datasheet, are taken for granted.

In the end, MEMS oscillators will have to prove themselves in each specific application, as the performance requirements per market are very different. However, in order to enter the high-end timing market, a MEMS oscillator will have to approach the phase noise requirements set by typical crystal oscillators of −105 dBc/Hz at 100 Hz, −135 dBc/Hz at 1 kHz, −155 dBc/Hz at 10 kHz, have a noise floor of −160 dBc/Hz for reference frequencies in the range of 10 MHz to 20 MHz, have power consumption below 3.5 mA, and have aging below ±1 ppm/year.

CONCLUSION

We believe we are the first group to demonstrate a MEMS oscillator comparable in performance to temperature-compensated crystal oscillators (TCXO) in frequency accuracy, temperature stability, and phase noise. The presented temperature-compensated MEMS oscillator (TCMO™) achieves a worst-case phase noise of –116 dBc/Hz at 1 kHz offset from the 123.9 MHz carrier, relating to a worst-case phase noise value of –135.6 dBc/Hz at 1 kHz offset at 13 MHz. The temperature drift of the MEMS oscillator is within ±2.5 ppm over the entire operating temperature range from –40°C to +85°C. Although the tuning of the oscillator frequency is analog, the compensation voltage is currently computed digitally and applied digitally with a DAC. Therefore, phase and frequency discontinuities exist for the current β-TCMO™. The fully integrated TCMO™ uses an analog temperature compensation similar to a TCXO and, therefore, does not experience the deterioration of phase noise and jitter nor exhibit sudden jumps in phase that plague commercially available fractional *N*-PLL based designs. Our future goal is to build on the TCMO™ timing platform and develop advanced high-performance timing solutions for additional timing applications.

REFERENCES

[1] C. S. Lam, 2008, *"A Review of the Recent Development of MEMS and Crystal Oscillators and Their Impacts on the Frequency Control Products Industry,"* in Proceedings of the IEEE International Ultrasonics Symposium, 2-5 November 2008, Beijing, China, pp. 694-704.

[2] M. E. Frerking, 1996, *"Fifty years of Progress in Quartz Crystal Frequency Standards,"* in Proceedings of the 1996 IEEE International Frequency Control Symposium, 5-7 June 1996, Honolulu, Hawaii, USA (IEEE 96CH35935), pp. 33-46.

[3] *http://www.sitime.com*

[4] *http://www.discera.com*

[5] W.-T. Hsu, 2009, *"Recent Progress in Silicon MEMS Oscillators,"* in Proceedings of the 40th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 2-4 December 2008, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 135-146.

[6] R. Henry and D. Kenny, 2008, *"Comparative Analysis of MEMS, Programmable, and Synthesized Frequency Control Devices Versus Traditional Quartz Based Devices,"* in Proceedings of the IEEE International Frequency Control Symposium, 19-21 May 2008, Honolulu, Hawaii, USA (IEEE CFP08FRE), pp. 396-401.

[7] B. Neubig, 2008, *"MEMS-Oscillators–Opportunities and Limitations"* (in German), **Markt & Technik,** No. 37, 28-29. (*http://www.axtal.com/info/MuT_37_08.pdf*)