MEMS Oscillators

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ABSTRACT

Microelectromechanical systems (MEMS) oscillators are now replacing quartz crystal oscillators. These new oscillators provide higher performance, new features, improved relaiability, shorter lead times, and reduced cost. This paper describes the design and construction of MEMS oscillators and presents data from the highest performance devices to date. They have frequency stability of ±0.5 parts per milions (ppm) from –40 to 85°C, random phase jitter of 0.5 ps RMS integrated from 12 kHz to 20 MHz, period jitter of 1.5 ps RMS, and Allan deviation under 5 parts per billion (ppb) at 0.1 to 10 second strides. Recent advances in MEMS resonators, temperature-to-digital converters (TDCs), and fractional synthesizers have enabled this performance. Additional capabilities supported by these innovations are highlighted, includeing digital controlled oscillators (DCXOs) and frequency selectable oscillators (FSXOs).

Keywords: MEMS, oscillators, timing, frequency reference, quartz crystal replacement.

1 INTRODUCTION

Precision oscillators drive almost all modern electronic systems to set the frequencies to which data is received and transmitted, radios are tuned, processors are driven, analog information is digitized, and date and time are measured. While these oscillators are a small part of systems, they are critical and without them building modern electronics would be impossible.

Oscillators are a multi-billion dollar industry which is presently dominated by quartz crystal technology. The importance and value of this industry has motivated the development of MEMS oscillators to replace quartz oscillators. The first publication in this field dates from 1967 [1] but only in the last five years have MEMS-based oscillators been commercially viable. In the last year commercial traction of MEMS oscillators has increased to the point that quartz oscillators may be seeing a sustained decline.

MEMS oscillators are built with silicon in standard CMOS fabs. They leverage advantages common to semiconductor products, such as miniaturization, rigorous quality control, and continuous performance improvement, to produce superior products at low cost. MEMS oscillators also employ modern circuit-centric architectures that support new functions and programmability.

Successful adoption of these new oscillators requires meeting or exceeding performance requirements that were defined for the legacy quartz products. Oscillator applications can be categorized based on their signal and device requirements. Common categories include high-speed communications systems that require very low jitter, radio frequency systems that require low phase noise, precision timing systems that require highly accurate frequencies, mobile clocking applications that require low power, and consumer applications that require low cost.

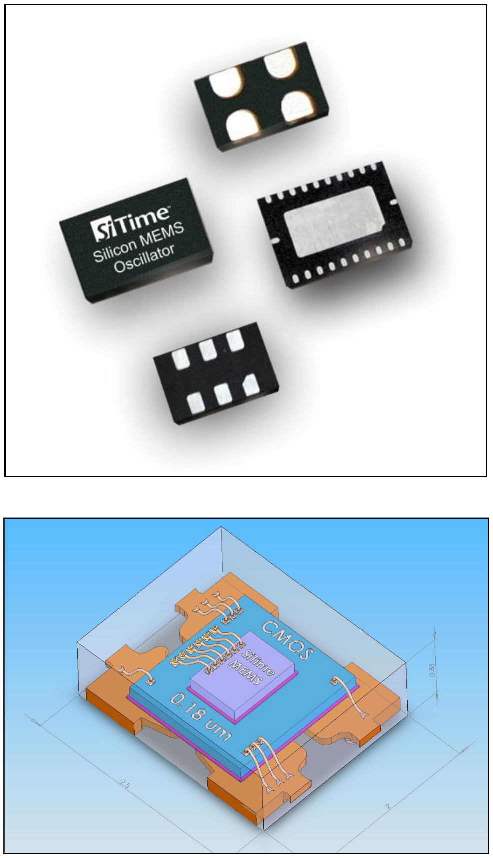


Figure 1: (a) Packaged MEMS oscillators, (b) Drawing of an oscillator’s iternal construction. © SiTime.

These categories are mostly exclusive. For instance the high-speed serial interfaces that require low jitter do not require low power. While handheld devices do not require the highest signal quality but do require low power to extend battery life.

The incumbent quartz technology has been optimized into a variety of products for these and other applications. They are available at a range of price points. Low jitter and high precision applications often require oscillators costing five to fifty dollars (and in a few cases hundreds to thousands of dollars) while consumer applications often require oscillators for tens of cents but can command high production volumes.

2 SYSTEM OVERVIEW

MEMS oscillators are built much like standard semiconductor ICs. Figure 1 shows the external appearance and internal construction of a MEMS oscillator. A MEMS resonator die is stacked on a CMOS die which is mounted on a lead frame. The MEMS die, CMOS die, and lead frame are electrically connected with wire bonds. The lead frame is molded in an array with other lead frames, singulated into an individual chip, and tested. The lead frame dimensions and solder pads match standard quartz oscillator form factors so that the MEMS oscillators can directly replace the incumbent products.

The resonators are encapsulated in hermetically sealed vacuum cavities inside the MEMS die [2]. Figure 2 shows an electron micrograph of a MEMS resonator that has been cleaved, exposing part of the resonator at the edge of the silicon, and also showing the top surface with electrical interconnect traces.

The resonator holds a precise frequency over variations in temperature, drive, stress, pressure, and other environmental influences. The resonator also provides a low phase noise signal. Phase noise is a measure of the impurity of the signal, and a lower phase noise vaule is better.

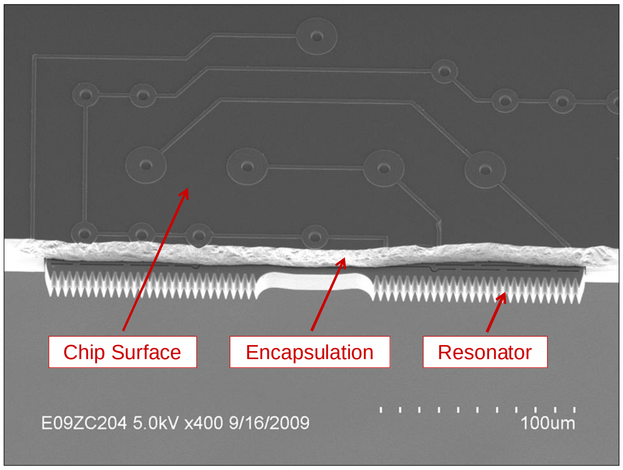


Figure 2: Electron micrograph of a resoantor. © SiTime.

CMOS circuits drive the resonator and translate the resonator frequency to a pre-programmed output frequency. The circuits are as important as the resonator in delivering the proper output signal, and while the whole device is called a MEMS oscillator it is the resonator and circuits together that determine the performance. The circuit architecture is shown in Figure 3 and represents a significant advance over the simpler circuits used in legacy quartz oscillators.

The circuits perform three primary functions. First, they drive the MEMS resonator into continuous oscillation to produce the MEMS reference frequency. Second, they measure the resonator temperature and together with a stored value for initial offset, they adjust the resonator frequency to a highly stable and accurate reference. Third, they shift that reference to a preprogrammed output frequency. The output frequency can be programmed from 200 kHz to over 500 MHz with ppm-level precision.

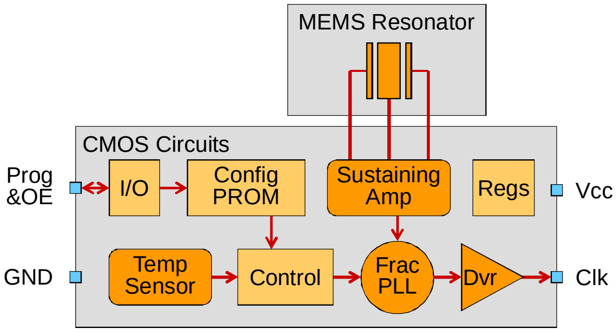


Figure 3: System architecture. © SiTime.

3 PERFORMANCE

The primary measure of an oscillator's performance is its frequency stability over temperature [3]. Oscillators with stability of better than about ±10 ppm are generally called temperature compensated oscillators, or TCXOs, to distinguish them from the more common oscillators, called XOs, that typically deliver ±20 to ±100 ppm stability.

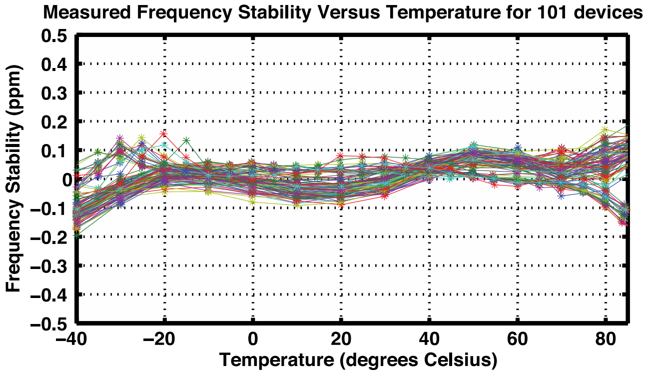
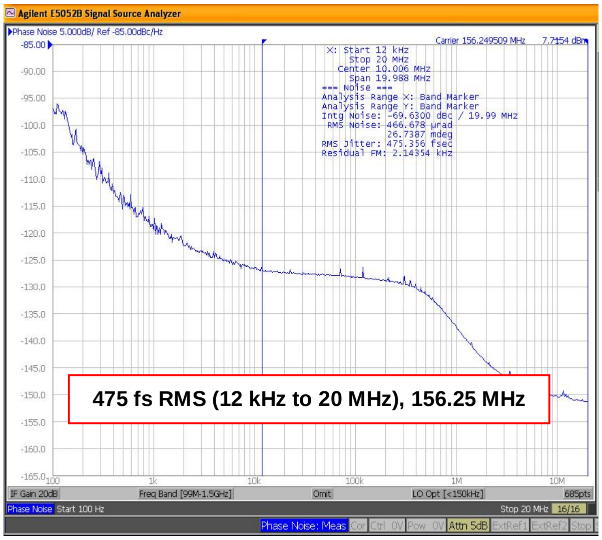


Figure 4: Frequency stability over temperature. © SiTime.

Figure 4 shows the frequency stability of oscillators swept over temperature from –45 to 85C. Their frequency error is less than ±0.2 ppm over the industrial temperature range. This performance is required in only a few applications. For example, GPS satellite positioning normally requires only ±0.5 ppm. Most consumer applications require 100x less precision, where ±20 to ±50 ppm is more common.

Phase noise is the next important parameter in oscillator performance [4]. This is a measure of the ratio of noise to signal powers (or of amplitudes) as a function of frequency. Figure 5 shows the phase noise of a MEMS oscillator at 156.25 MHz, a common reference frequency for high-speed serial interfaces. This phase noise is sufficiently low for many RF applications, including the RF references in cell phones.



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X: Start 12 kHz
     Stop 20 MHz
   Center 10.006 MHz
     Span 19.988 MHz
=== Noise ===
Analysis Range X: Band Marker
Analysis Range Y: Band Marker
Intg Noise: -69.6300 dBc / 19.99 MHz
 RMS Noise: 466.678 µrad
            26.7387 mdeg
RMS Jitter: 475.356 fsec
Residual FM: 2.14354 kHz
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Figure 5: Phase noise and integrated jitter. © SiTime.

One can integrate phase noise across an offset frequency to derive the integrated phase jitter. This is a measure of the timing error in a clock compared to an ideal but unobtainable clock. The standard integration range for telecom applications is 12 kHz to 20 MHz, and commonly the integrated jitter is required to be less than 1.0 picosecond [5]. The MEMS oscillator signal shown in Figure 5 has an integrated jitter of 0.475 picoseconds [6].

Yet another important parameter is an oscillator's stability over a short period of time. This is quantified in a measurement called Allan deviation, which is the statistical variation between frequency measurements at a repeating time step, called the stride. The Allan deviation of these MEMS oscillators for strides of 0.1, 1.0 and 10 seconds is less than 5 ppb. One can interpret this as meaning that the frequencies measured each 1.0 second, for example, are statistically equal to one another to within 5 ppb.

This stability is needed in only a few applications, for instance time references in cell phone base stations. An important emerging application is maintaining time references in femtocells, which are small base stations that will be deployed in homes and businesses to provide local cell phone connectivity. The clocks in standard base stations can be expensive and cost hundreds of dollars, while those in femtocells must still deliver exceptional performance but cost only a few dollars. MEMS oscillators will play a vital role in this application.

4 ADDITIONAL CAPABILITY

MEMS oscillators are actually frequency generators rather than simple oscillators. Simple oscillators take a single reference frequency from a resonator and drive that frequency to their outputs. MEMS oscillators have the circuitry and control intelligence to translate from one frequency to another and to precisely trim that frequency.

Many applications require oscillators that supply an adjustable frequency. These are commonly called voltage controlled oscillators (VCXOs). They are used to match a local clock to an external clock, for instance to match the rate that data is received on a fiber optic link to that at which it is transmitted. In VCXOs a voltage applied to a control pin adjusts the oscillator's output frequency, typically by ±10 to ±100 ppm. Both quartz and MEMS oscillators provide this capability, but MEMS also provide digitally controlled oscillators (DCXOs). These devices receive a digital data stream and adjust their output frequencies with ppb resolution and ranges programmable from tens to over a thousand ppm. This is valuable because (1) the larger adjustment ranges are not possible in quartz but often needed, (2) the analog voltage control in VCXOs often contribute noise to the output frequency but digital control in DCXOs do not, and (3) the digital control is usually simpler and lower cost for the system.

Spread spectrum oscillators modulate their output frequencies to reduce transmitted RF interference. This is virtually always done via frequency adjusting electronics, and in the case of quartz oscillators requires additional circuitry. This circuitry is intrinsically available in MEMS oscillators and therefore the function is more readily and better provided.

Frequency selectable oscillators (FSXOs) allow choosing between multiple output frequencies under digital control. This is not generally available with quartz oscillators and thus not commonly used. However MEMS oscillators readily support this functionality. FSXOs can be used to auto-configure variable frequency systems, for instance to adapt to serial interface standards with differing baud rates.

These are examples of what new MEMS oscillator technology is bringing to electronic systems. With these features it is possible for system designers to provide functions that cannot be delivered with fixed-frequency incumbent oscillators. In the future we will see these special functions expanded.

5 COMMERCIAL SUCCESS

MEMS oscillators are now seeing significant comercial traction. SiTime (the author's company and the leading provider of MEMS oscillators) recently announced it had shipped its 100 millionth unit. Figure 6 shows SiTime's annual unit sales over the past five years roughly doubling each year. This growth rate is enabled by a continuous introduction of new oscillators that provide ever better performance while opening new applications.

Recently introduced low jitter oscillators have opened applications in high-speed data communications, data storage, and servers. Recently introduced TCXOs are finding applications in fiber optic transceivers, satellite position systems, network clocks, and femtocells.

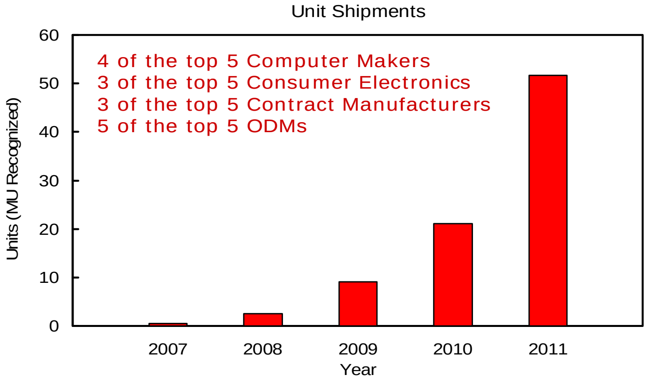

Figure 6: Unit shippments of SiTime parts. © SiTime.

Low power MEMS oscillators have seen wide and growing adoption in still and video cameras, LAN equipment, laptop computers, tablets, set top boxes, and various consumer-level devices.

We believe that virtually all oscillator applications will convert to MEMS. There are no natural barriers or limits to the technology that preclude this. On the high-performance end the capabilities will likely exceed quartz, and on the consumer end the costs are lower than quartz.

6 CONCLUSIONS

The introduction of MEMS oscillators is impacting the quartz oscillator industry. MEMS oscillators are delivering performance levels tailored for a wide range of applications. Significant commercial traction has been seen in consumer products and data storage, while high-speed networking and high precision time keeping are adopting newly introduced products. With recent exponential growth, MEMS oscillators promise to displace quartz oscillator as the dominant timing reference.

7 ACKNOWLEDGEMENTS

M. Perrott, F. Lee, and members of SiTime's staff contributed significant material for this paper.

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