NASA Electronic Parts and Packaging Program

Effects of Temperature on the Performance and Stability of Recent COTS Silicon Oscillators

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Background

Computers, microprocessors, and data-acquisition instruments rely on accurate timing signals for proper operation. Ceramic resonators and crystal oscillators are traditionally used to provide such signals due to their accuracy, availability, and low cost. They are, however, sensitive to vibration and shock, require external components, and prone to electro-magnetic interference (EMI). Over the last few years, silicon oscillators, including those built using MEMS (Micro-Electro-Mechanical Systems) technology, began to be offered by a few companies as commercial-off-the-shelf (COTS) parts as potential replacement for these traditional crystal oscillators in providing timing signals in digital and analog circuits. These quartz-free oscillators cover a wide frequency range, offer great tolerance to shock and vibration, and are immune to electro-static discharge. They are generally supplied at specific factory-trimmed frequencies or require few or no external components for frequency determination, exhibit fast startup times, consume very low current, and are reported to provide extremely stable output frequency.

Although the industrial-grade parts of the majority of these oscillators are specified for temperature operation between -40 °C to +85 °C, the small size of these silicon-based oscillators; in particular the MEMS type, along with their reliability and thermal stability make them ideal candidates for use in space exploration missions. Limited data, however, exist on the performance and reliability of these devices under operation in applications where extreme temperatures or thermal cycling swings, which are typical of space missions, are encountered. This report presents the results of the work obtained on the evaluation of some of these recently-introduced COTS silicon oscillators under extreme temperatures.

Test Procedure

Silicon oscillators from five manufacturers were selected for evaluation in this work. Table I shows some of the manufacturer's specifications for these device [1-5]. While some had a fixed frequency, others required the use of a set resistor to obtain the desired frequency. Performance characterization of each oscillator was obtained in terms of its output frequency, duty cycle, rise and fall times, and supply current at specific test temperatures. Restart capability at extreme temperatures, i.e. power switched on while the device was soaking at extreme (hot or cold) temperature, was also investigated. The effects of thermal cycling under a wide temperature range on the operation of these silicon oscillators were also investigated. Each oscillator was subjected to a total of 12 cycles within a temperature range (specific to each device) at a temperature rate of 10 °C/minute and a soak time of 20 minutes at the temperature extremes.

Table I. Manufacturer's specifications of silicon oscillators [1-5].

Parameter	**LTC6906H**	**ASFLM1**	**EMK21**	**STCL1100**	**SiT1100AI**
Manufacturer	Linear Tech	Abracon	Ecliptek	STMicroelectronics	SiTime
Type	Si	Si MEMS	Si MEMS	Si	Si MEMS
Oper. volt (V)	2.25 to 5.5	3.0	1.8	5.0	1.8
Freq. (MHz)	0.01 to 1	1.8432	1	10	1
Oper. temp. (°C)	-40 to +125	0 to +70	-40 to +85	-20 to +85	-40 to +85
Duty cycle (%)	45 to 55	45 to 55	50 ±5	40 to 60	40 to 60
Freq. tol. (ppm)	[drift±0.005%/°C]	±50	±50	[accuracy ±1.5 %]	±50
Output t_R/t_F (ns)	25	5	2	5	2
Package	Plastic SOT-23	Plastic QFN	Plastic QFN	Plastic SOT23-5L	Plastic QFN
Part #	LTC6906HS6	ASFLM1-1.8432-C	EMK21H2H-1.000M	STCL1100YBF-CWY5	SiT1100AI-33-18S
Lot number	5K77 / LTBJN	AB C0729	0020	10A Y832	20643

Test Results

Temperature Effects

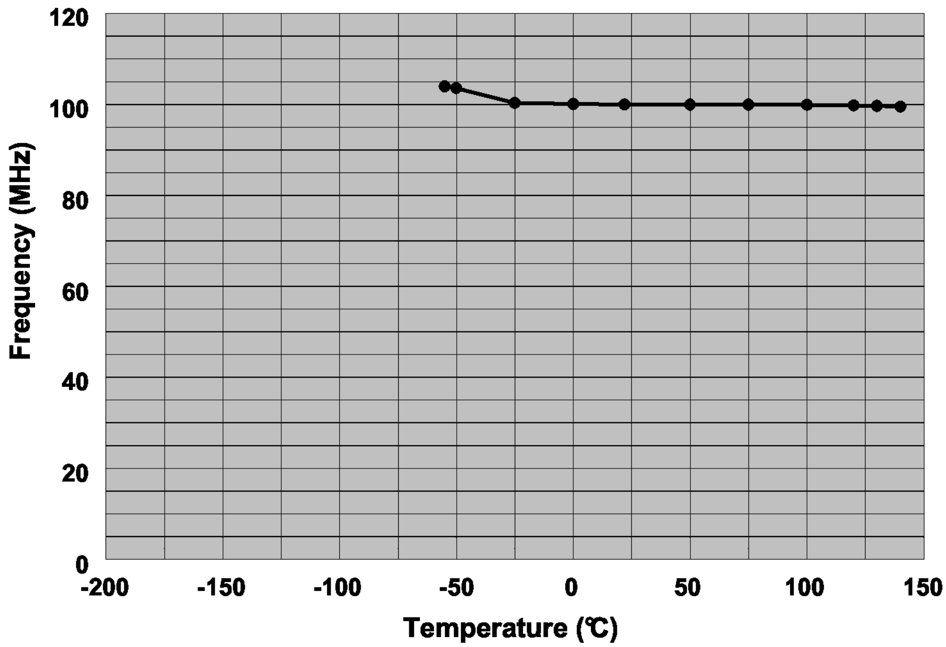
The following remarks need to be pointed out prior to presenting the experimental findings in this report:

- The data documented in this report is based only on a preliminary work that was performed to gain insight on the potential of the investigated devices for use in extreme temperature environments. It should not be interpreted, therefore, as a gauge of reliability or usefulness for long term use of these parts. Additional comprehensive testing is required to address such concerns.

- The test temperature range differed for each of the five oscillators, and it was based on performance stability of the device-under-test. Thus, all five devices were subjected to testing in a temperature regime that exceeded their specified operating range where normal operation was demonstrated by all oscillators.

- It should be noted that the findings reported here are based purely on in-house experimental work and the results, therefore, should not be do not construed as NASA endorsement of any or all of these products but rather used as a guide to aid in the proper selection of parts for use in specific applications.

The LTC6906 silicon oscillator exhibited excellent stability in its output frequency in the temperature range between -25 °C and +140 °C, as shown in Figure 1. As the test temperature was lowered from - 25 °C to -55 °C, however, the oscillator continued to operate but its frequency began to increase with decrease in temperature. This increase in frequency at - 55 °C amounted only to about 4% of its room temperature value. At temperatures below -55 °C, the oscillator began to exhibit instability in its operation. In terms of duty cycle, the output signal did not display any significant change over the test temperature range between -55 °C and +140 °C, as depicted in Figure 1.



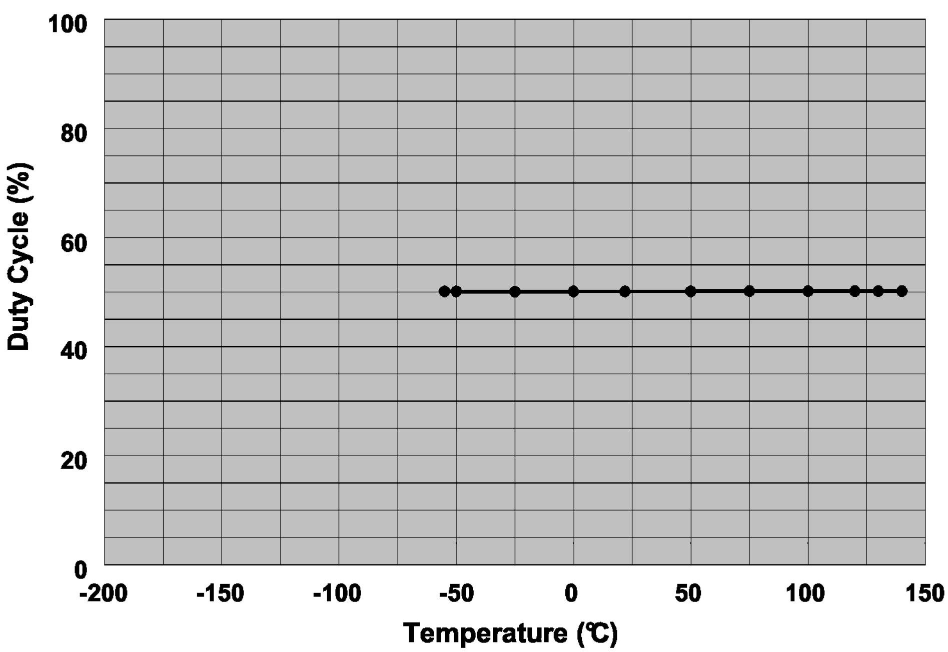
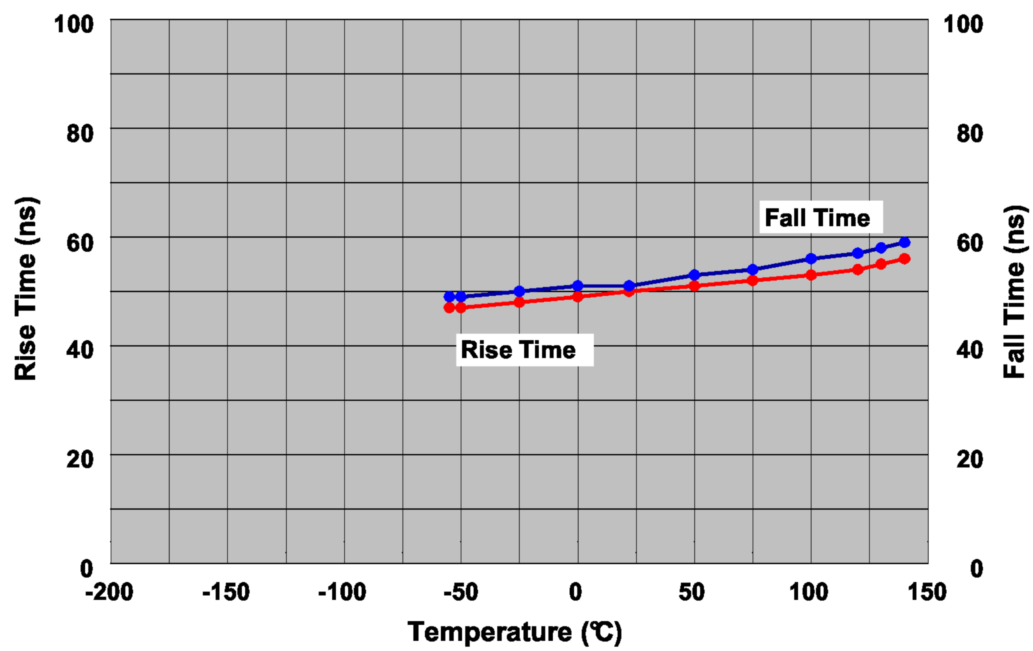


Figure 1. Frequency and duty cycle of LTC6906 oscillator as a function of temperature.

The rise and fall times of the output signal of the LTC6906 oscillator displayed weak dependence on temperature as shown in Figures 2. It can be seen that both exhibited very slight decrease with decrease in temperature from room temperature, and the reverse was true when the circuit was exposed to high temperatures. The quiescent supply current of this oscillator, which is infinitesimally small as it falls within the micro-amp range, increased very slightly with decrease in temperature from room temperature. When the temperature was increased beyond room temperature, the minute current attained even lower values, as depicted in Figure 2.



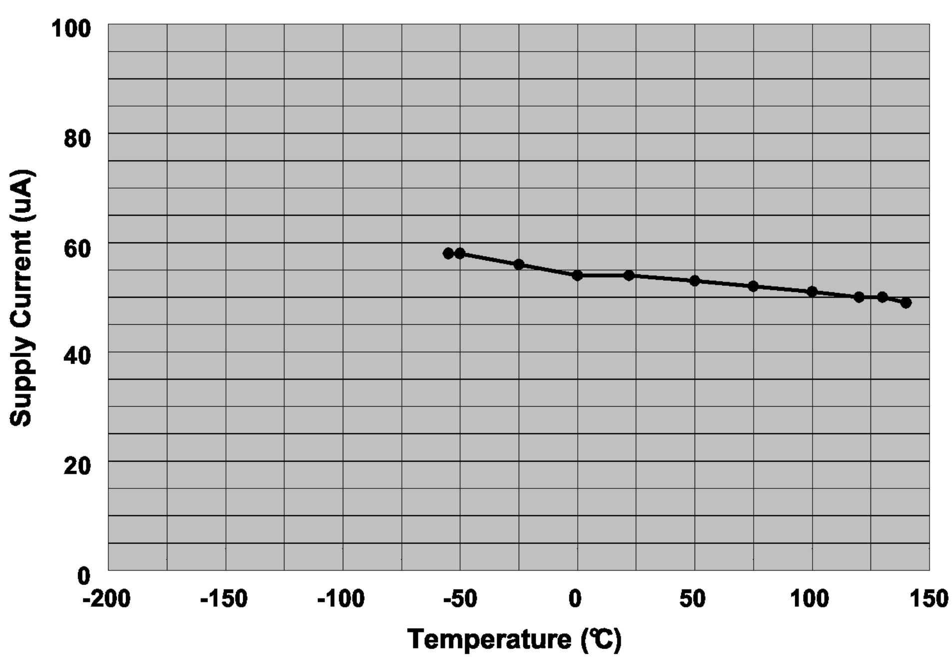


Figure 2. Rise & fall times, & supply current of LTC6906 oscillator versus temperature.

The ASFLM1 silicon MEMS oscillator exhibited excellent stability in its operation as its output frequency retained its 1.84 MHz value throughout the temperature range of -190 °C to +140 °C, as shown in Figure 3. Similarly, the duty cycle of this MEMS oscillator output signal, also shown in Figure 3, did not display any significant change over this test temperature range.

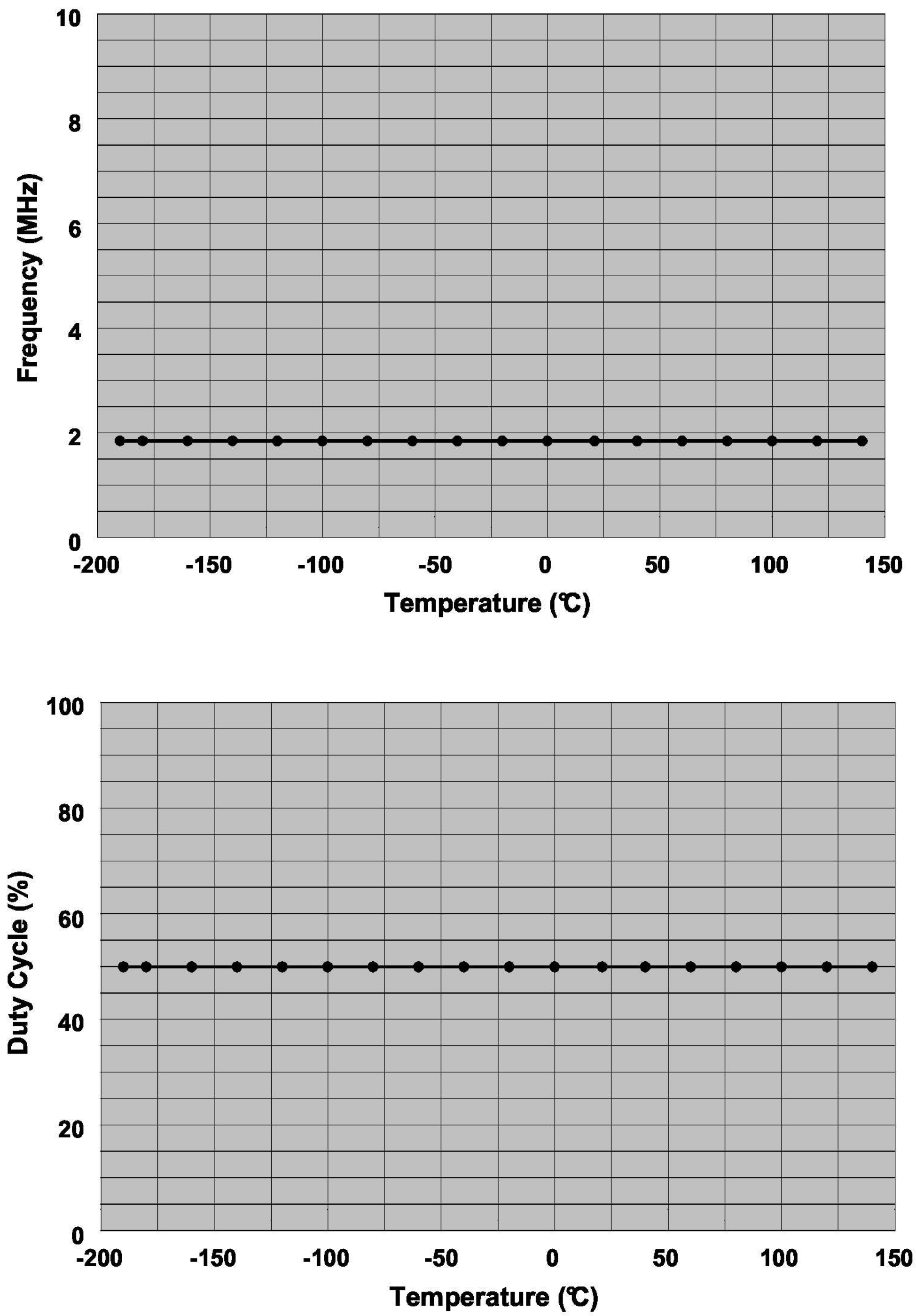


Figure 3. Frequency and duty cycle of ASFLM1 oscillator as a function of temperature.

The output's rise and fall times of the ASFLM1 oscillator displayed similar dependence on temperature as both were found to exhibit gradual but very small reduction in their values as temperature was decreased below room temperature; and the reverse was true when the circuit was exposed to high temperatures. These changes in the rise and fall time of the oscillator's output signal are shown in Figure 4. The supply current of this oscillator, which is also shown in the same figure, tended to exhibit an almost linear dependence on the test temperature. For instance, while the current exhibited a gradual drop in value as test temperature was decreased from room to cryogenic temperatures; it increased slightly as temperature was varied from 22 °C to 140 °C.

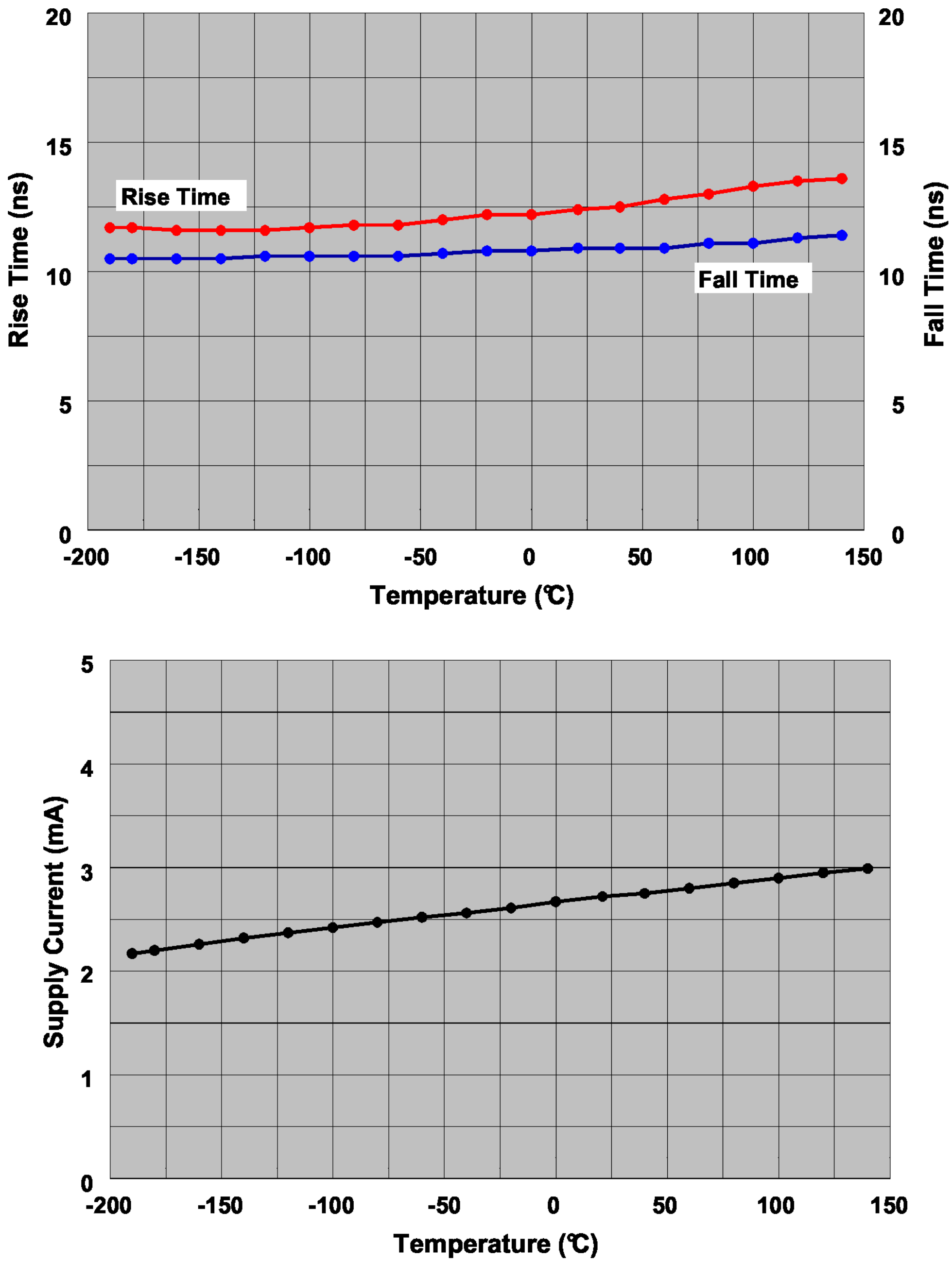


Figure 4. Rise & fall times, & supply current of ASFLM1 oscillator versus temperature.

The EMK21 MEMS oscillator exhibited excellent stability with variation in temperature between -112 °C and +110 °C. Throughout this range, the frequency exhibited hardly any change with temperature, as shown in Figure 5. As the temperature was reduced below -112 °C, however, the oscillator began to behave erratically as its output became unstable and the frequency fluctuated continuously. This instability was found to be transitory as the oscillator recovered when temperature was increased to about -112 °C and above. High temperature testing was limited to +110 °C because the device is rated for -40 °C to +85 °C operation. Nonetheless, the chip produced very stable output in a temperature range that exceeded both ends of the manufacturer's specified limits. Similar to frequency, the duty cycle of the output did not display any significant change over the test temperature range between -112 °C and +110 °C, as depicted in Figure 5.

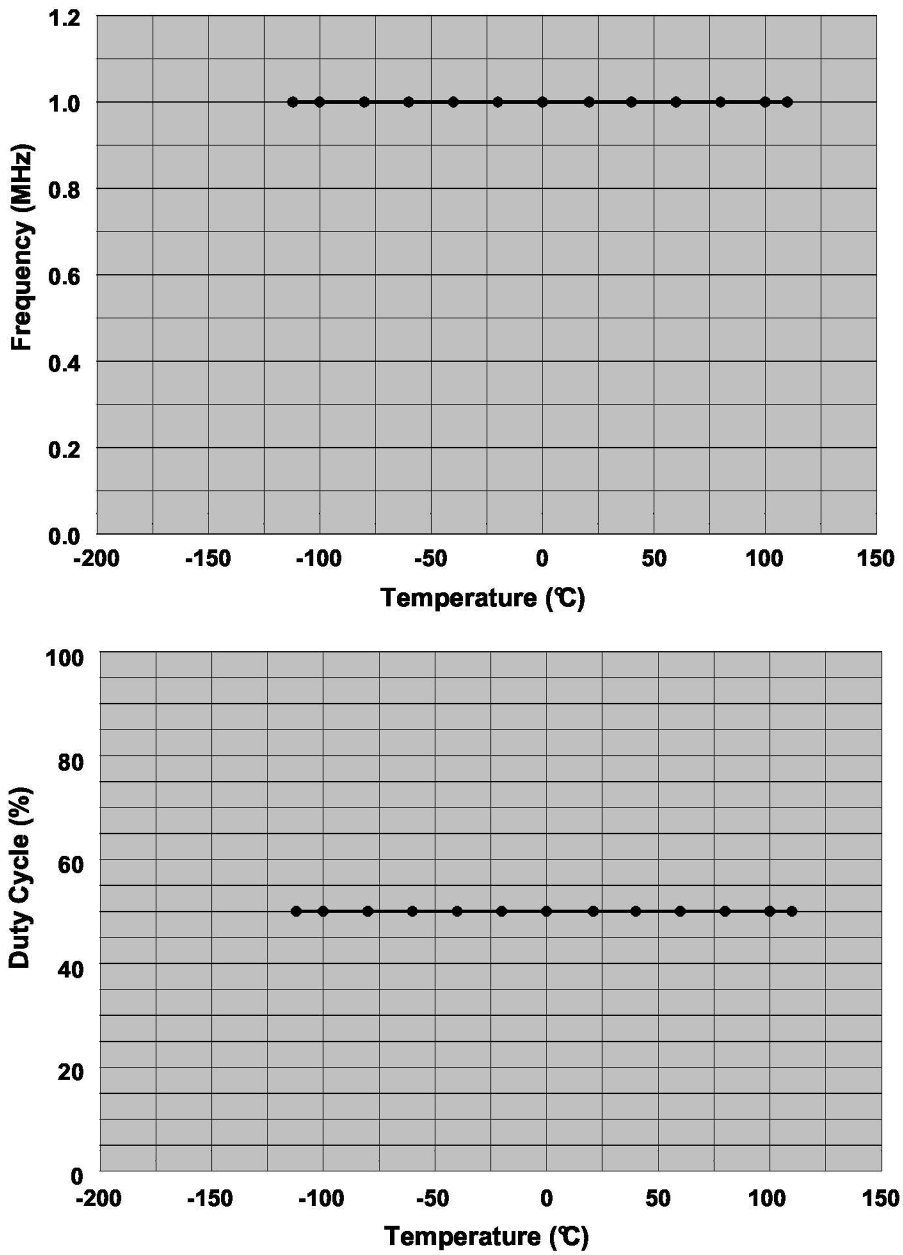


Figure 5. Frequency and duty cycle of EMK21 oscillator as a function of temperature

Figure 6 shows the rise time as well as the fall time of the output signal of the EMK21 MEMS oscillator as a function of temperature. Both of these characteristics were found to display similar but weak dependence on temperature as they underwent gradual but very small reduction in their values as temperature was decreased below room temperature; and the trend reversed as temperature was increased. Similar behavior was experienced by the supply current of this oscillator with change in temperature as shown in Figure 6.

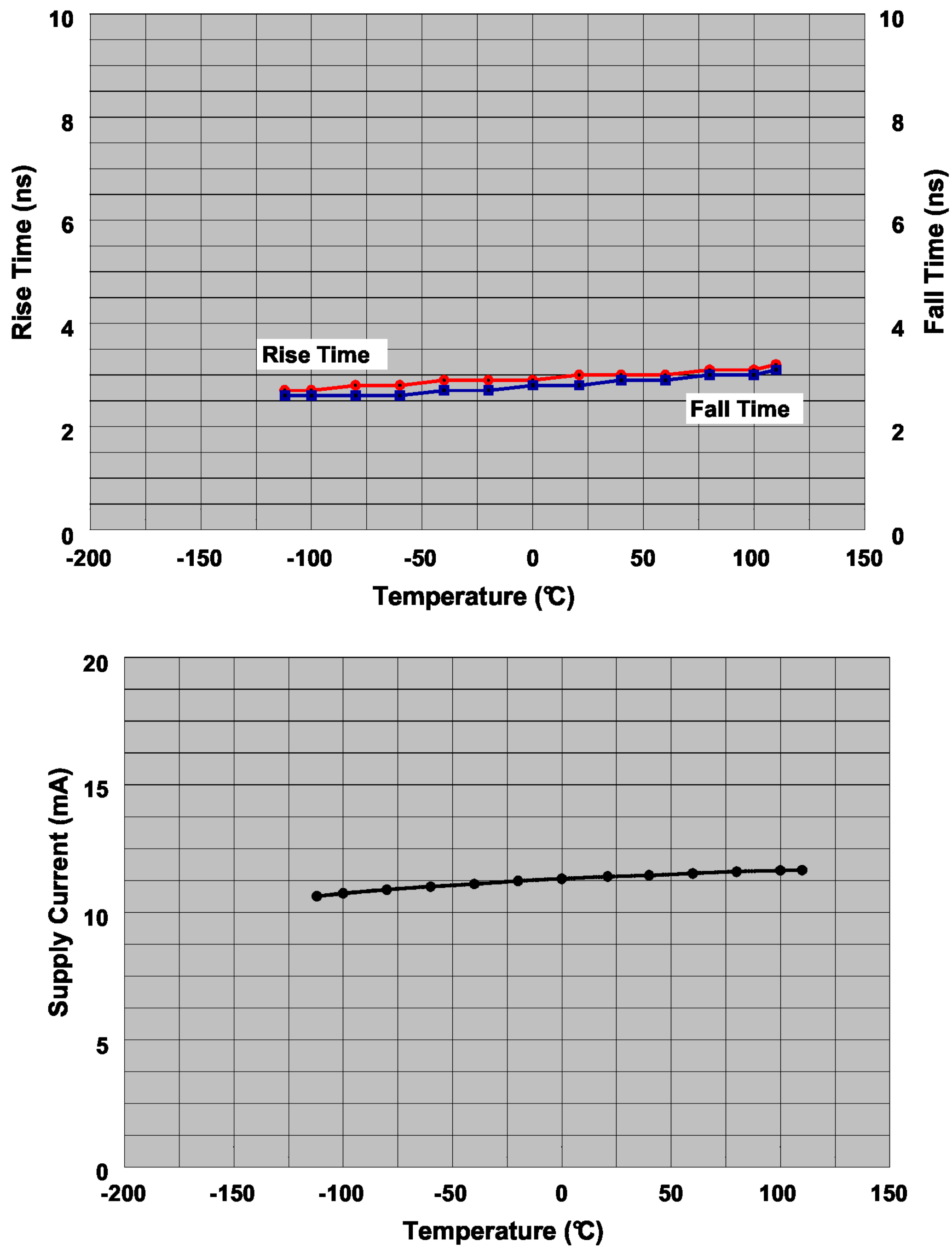


Figure 6. Rise & fall times, & supply current of EMK21 oscillator versus temperature.

The STCL1100 silicon oscillator exhibited very good stability in its output within the temperature range of about -50 °C to +130 °C, as shown in Figure 7. The upper temperature of +130 °C was well above the +85 °C specification temperature. At temperatures below -50 °C, however, the oscillator began to exhibit a decrease in frequency as temperature was decreased further. The intensity of this decrease ranged from being slight between -50 °C to -125 °C to becoming more intense as temperature was further lowered toward the cryogenic test point of -195 °C. For example, while the output frequency changed by only about 1.8% between -50°C and +130 °C, it decreased by about 11% between -50°C and -125 °C, and attained as much as 49% drop at -195 °C. The duty cycle of the output signal of this oscillator displayed minor variation over the test temperature range as its value swung between 43% and 48% at the test temperatures of +130 °C and -195 °C, respectively, as depicted in Figure 7.

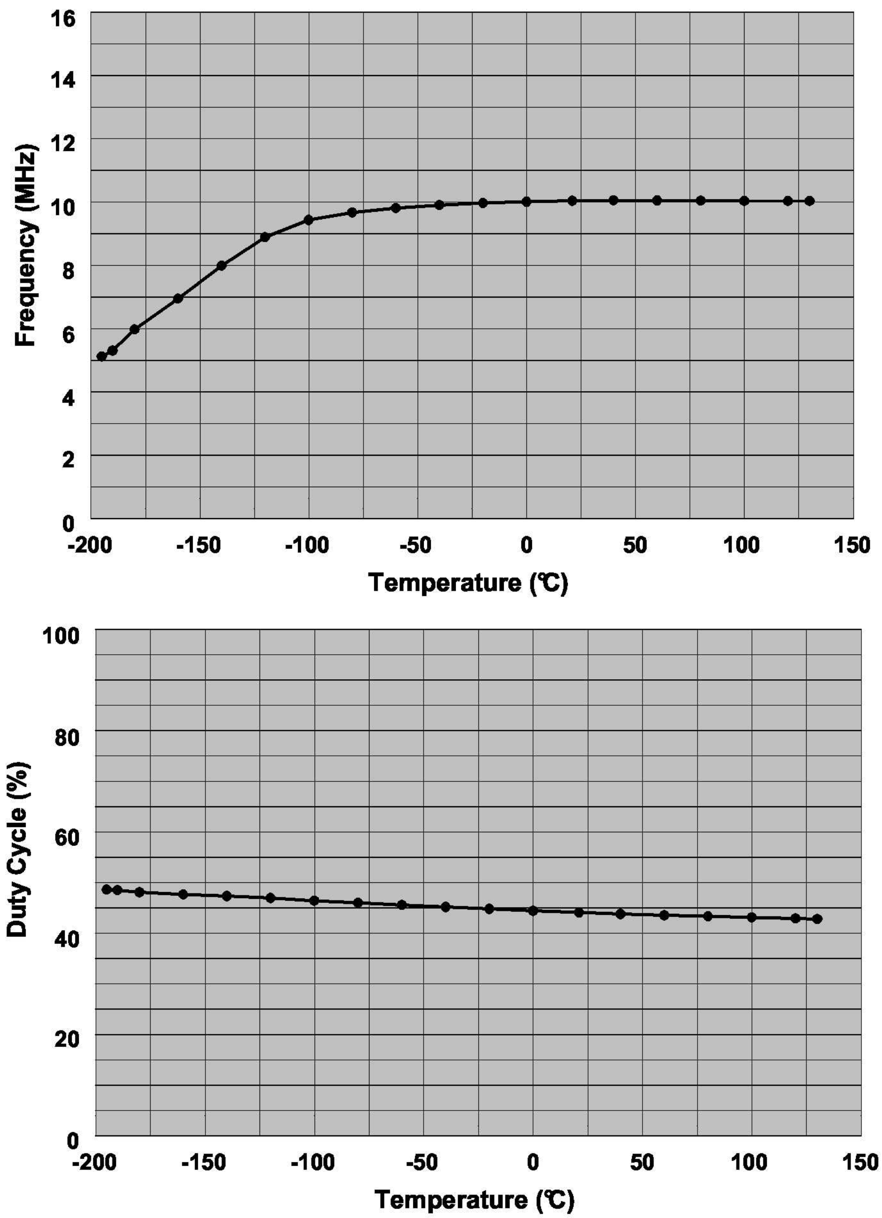


Figure 7. Frequency and duty cycle of STCL1100 oscillator as a function of temperature

The rise and fall times of the STCL1100 oscillator's output signal displayed similar dependence on temperature. Both of these characteristics were found to exhibit an increase in their values as the test temperature moved away in either direction from room temperature. This increase in the rise as well as the fall time was more profound at cryogenic temperatures than at the other band as shown in Figure 8. While the supply current seemed to exhibit a gradual but very slight increase as the test temperature was increased from ambient to higher temperatures, it underwent a decrease in its value as the silicon oscillator was subjected to test temperatures lower than room temperature. This decrease in the supply current with temperature was more noticeable in the temperature vicinity of -125 °C to -195 °C, as depicted in Figure 8.

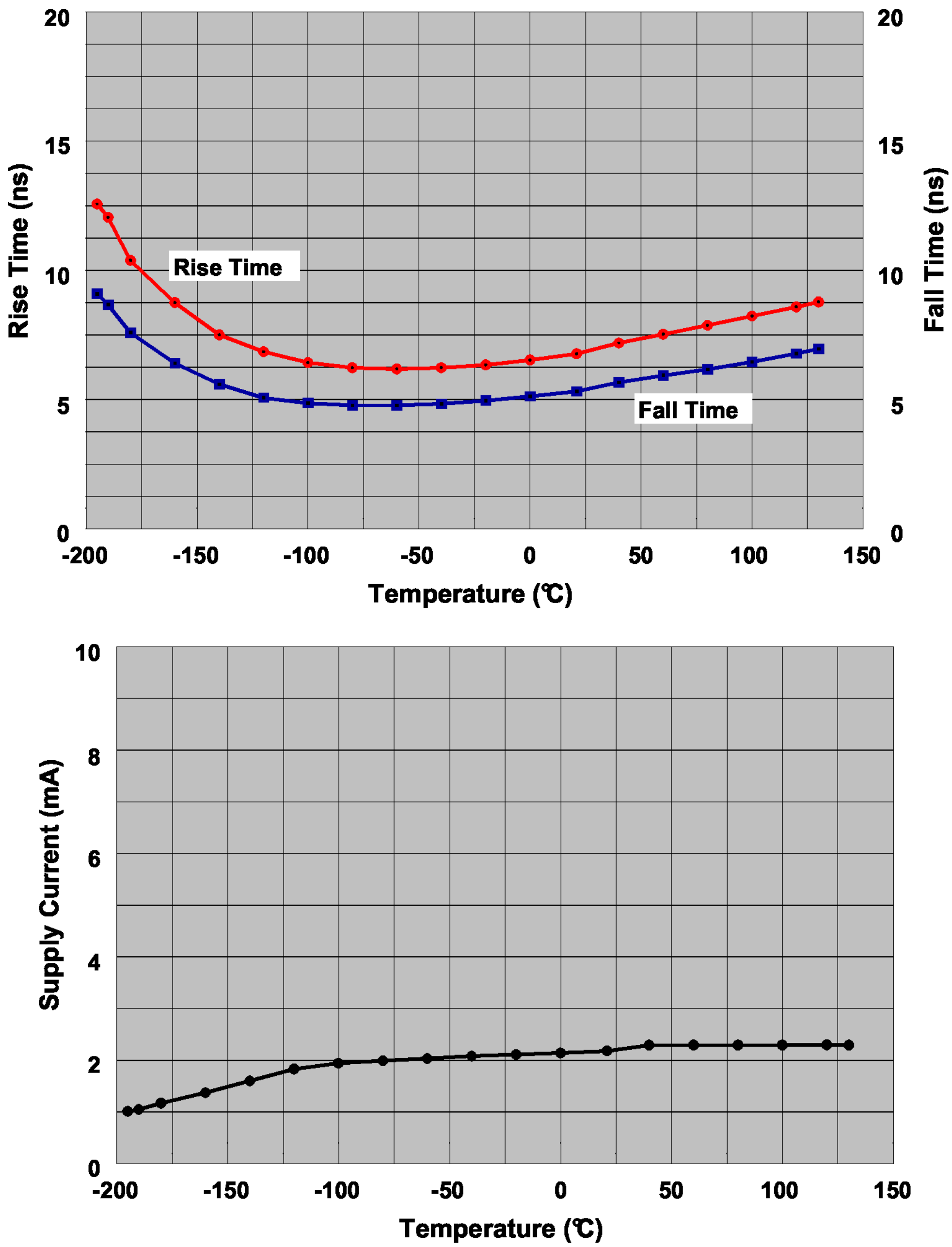


Figure 8. Rise & fall times, & supply current of STCL1100 oscillator versus temperature.

The SiT1100AI silicon MEMS oscillator exhibited excellent stability in its output frequency with variation in temperature between -110 °C and +100 °C. Throughout this range, the frequency exhibited hardly any change with temperature, as shown in Figure 9. As the test temperature was reduced below -110 °C, however, the oscillator continued to deliver an output but with continuously changing frequency. Similar to frequency, the duty cycle of the output signal did not display any significant change over the test temperature range between -110 °C and +100 °C, as depicted in Figure 9.

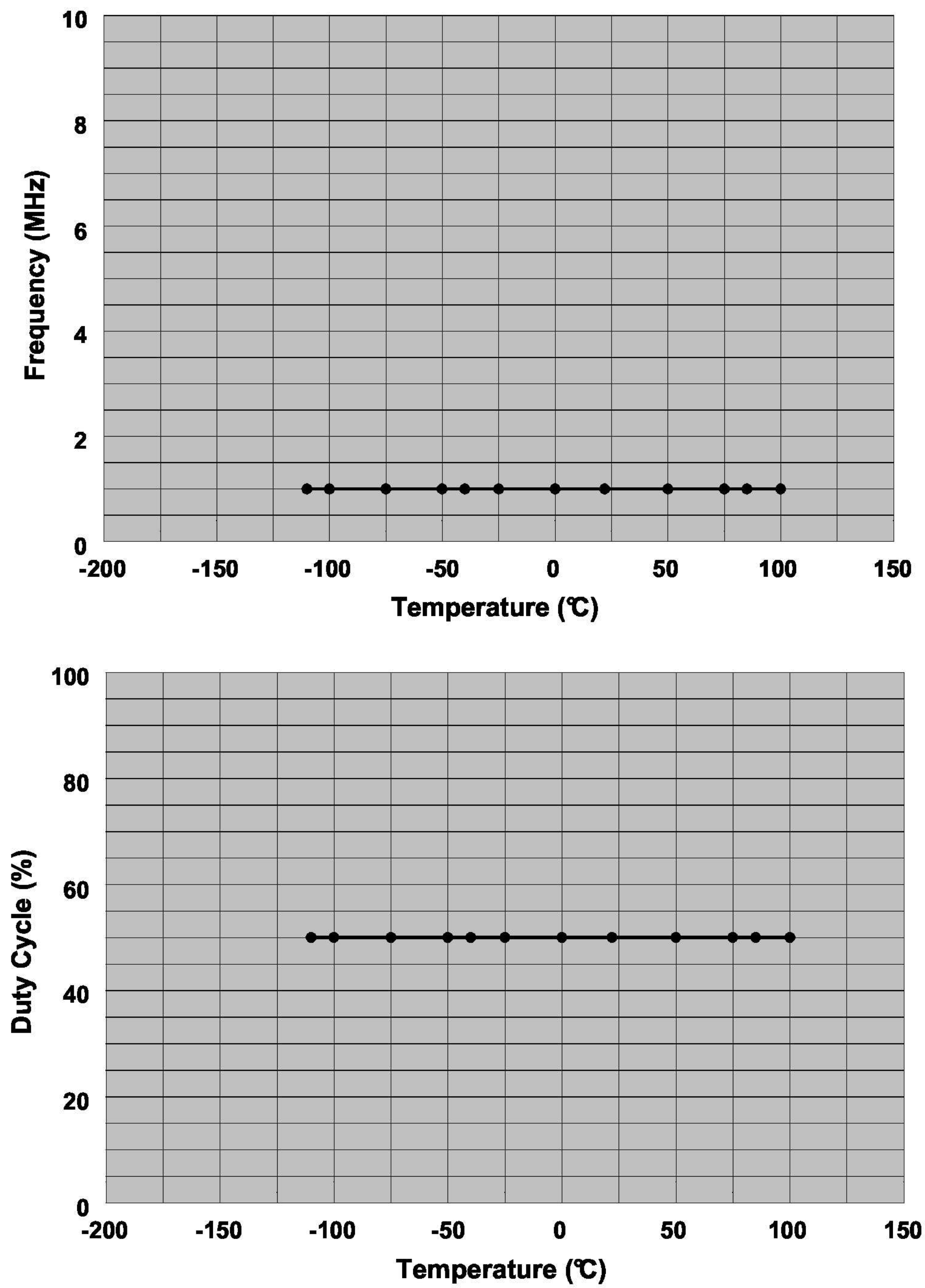
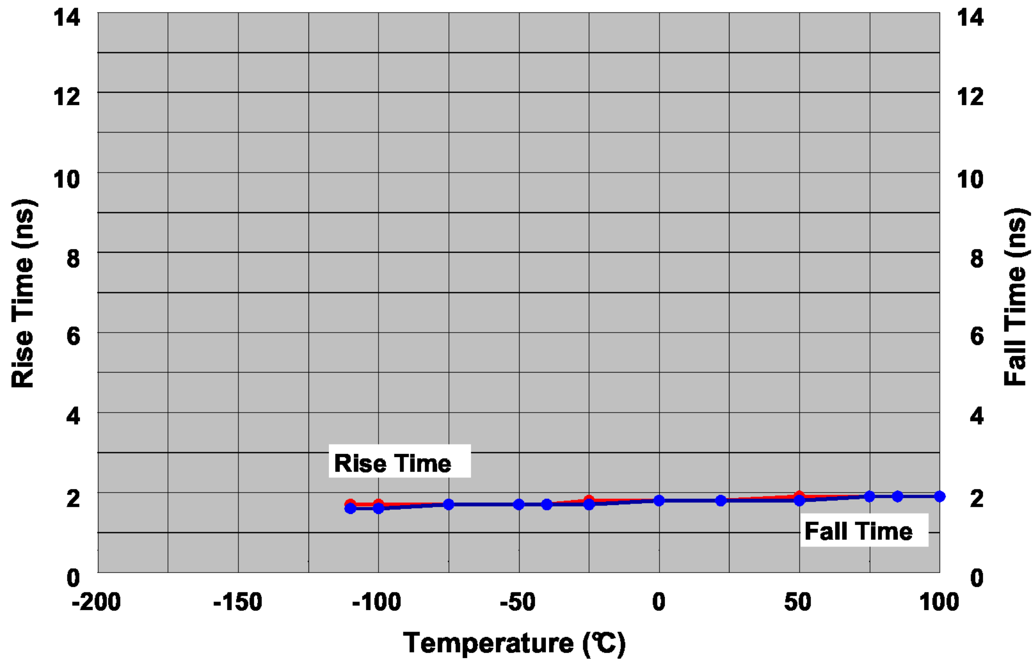


Figure 9. Frequency and duty cycle of SiT1100AI oscillator as a function of temperature.

The rise time as well as the fall time of the output signal of the SiT1100AI silicon MEMS oscillator displayed similar but very weak dependence on temperature. Both of these characteristics were found to exhibit linear, albeit minute, dependency on temperature throughout the range of -110 °C to 100 °C as shown in Figure 10. The supply current of the oscillator, which is also shown in the same figure as a function of temperature, was found to remain steady between the test temperatures of 25 °C to 100 °C but it experienced small and gradual reduction in its magnitude as the temperature was decreased below room temperature.



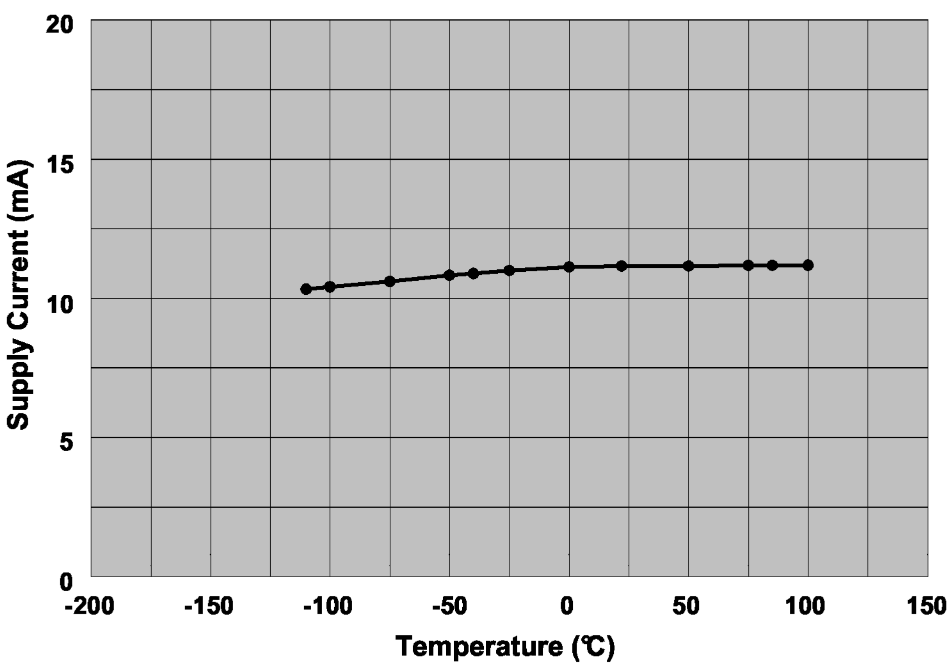


Figure 10. Rise & fall times, & supply current of SiT1100AI oscillator vs. temperature.

Re-Start at Extreme Temperatures

Re-start capability of all these silicon oscillators was investigated at the extreme (high and low) test temperatures at which each specific oscillator maintained stable operation. Each oscillator chip was allowed to soak separately at those two extreme temperatures, with electrical power off for at least 20 minutes. Power was then applied to the circuit, and measurements of the oscillator's output waveform characteristics and frequency were recorded. Each one of these five silicon oscillators successfully operated under either cold- or hot-start, and the data obtained, for a given device, was similar to those obtained earlier at these respective temperatures.

Effects of Thermal Cycling

The effects of thermal cycling under a wide temperature range on the operation of the silicon oscillators were investigated by subjecting each device to a total of 12 cycles within the temperature range where the device-under-test exhibited stable operation. Although the 12-cycle activity is by no means considered as a representative of accelerated or life testing to determine reliability of the device-under-test, it provides, nonetheless, some preliminary insight on the effect of thermal cycling on its behavior. During this cycling activity, a dwell time of 20 minutes was applied at the extreme temperatures. Post-cycling measurements on the characteristics of each oscillator were then performed at selected test temperatures utilizing a soak time of 20 minutes prior to recording any data. Table II lists these data along with those obtained before cycling. A comparison between pre- and post-cycling data, for all 5 oscillators, reveals that none underwent any significant changes in the operational characteristics due to this limited cycling. The thermal cycling also appeared to have no effect on the structural integrity of these devices as no structural deterioration or packaging damage had occurred.

Comparison of Performance of Oscillators

All five oscillators exhibited operation in a temperature range that exceeded their individual specified region. The temperature range for which stability was maintained differed from one device to another. While some displayed excellent stability throughout the whole test temperature range, the operation of others became unsteady at certain temperature test points as was reflected by fluctuation in the output frequency or distortion of the output waveform. Such temperature-induced changes were not permanent as the affected oscillators completely recovered upon removal of the thermal stress.

Figure 11 shows normalized frequency as a function of temperature for the five SI oscillators. The STCL1100 oscillator had a large frequency drop with decreasing temperature that made it a poor device for low temperature operation. Figure 1 had shown that the LTC6906 oscillator was stable to -25 °C, but Figure 1 and Figure 11 showed that at -55 °C the LTC6906 oscillator started to display an undesirable increase in frequency.

Figure 12 shows the three SI oscillators that were most frequency stable devices over a broad temperature range. The ASFLM1 oscillator operated over the widest temperature range from -190 °C to +140 °C. One must note carefully the vertical scale in Figure 12 to see that the ASFLM1 was quite frequency stable. The EMK21 and the SiT1100AI were very comparable in excellent frequency stability, and both operated over a very similar temperature range.

Table II. Pre- and post-cycling characteristics of the silicon MEMS oscillator.

Device	T(°C)	Cycling	f (MHz)	Duty cycle (%)	T_{rise} (ns)	T_{fall} (ns)	I_S (mA)
LTC6906	22	pre	99.990	50.12	50	51	0.054
		post	99.981	50.11	49	51	0.054
	-55	pre	103.964	50.15	47	49	0.058
		post	103.639	50.13	47	50	0.058
	+140	pre	99.485	50.17	56	59	0.049
		post	99.473	50.18	55	58	0.049
ASFLM1	22	pre	1.8432	49.94	49.94	12.4	10.9
		post	1.8432	49.94	49.94	12.0	10.4
	-190	pre	1.8469	49.92	49.92	11.7	10.5
		post	1.8467	49.93	49.93	11.4	10.1
	+140	pre	1.8425	49.94	49.94	13.6	11.4
		post	1.8426	49.94	49.94	13.5	11.2
EMK21	22	pre	1.00002	50.04	3.0	2.8	11.40
		post	1.00000	50.04	2.9	2.8	11.29
	-112	pre	0.99987	50.02	2.7	2.6	10.63
		post	0.99987	50.02	2.6	2.5	10.56
	+110	pre	1.00001	50.05	3.2	3.1	11.65
		post	1.00001	50.05	3.1	3.0	11.63
STCL1100	21	pre	10.0413	44.09	6.77	5.31	2.18
		post	10.0290	44.03	6.86	5.36	2.20
	-195	pre	5.1197	48.62	12.56	9.09	1.01
		post	5.1159	48.67	12.67	9.19	1.03
	+130	pre	10.0322	42.80	8.78	6.96	2.29
		post	10.0312	42.80	8.66	6.84	2.28
SiT1100AI	21	pre	1.00000	50.03	1.8	1.8	11.15
		post	1.00001	50.03	2.0	2.1	11.20
	-110	pre	0.99988	50.02	1.7	1.6	10.32
		post	0.99992	50.02	1.8	1.8	10.40
	+100	pre	0.99998	50.04	1.9	1.9	11.19
		post	0.99998	50.04	1.8	1.8	11.21

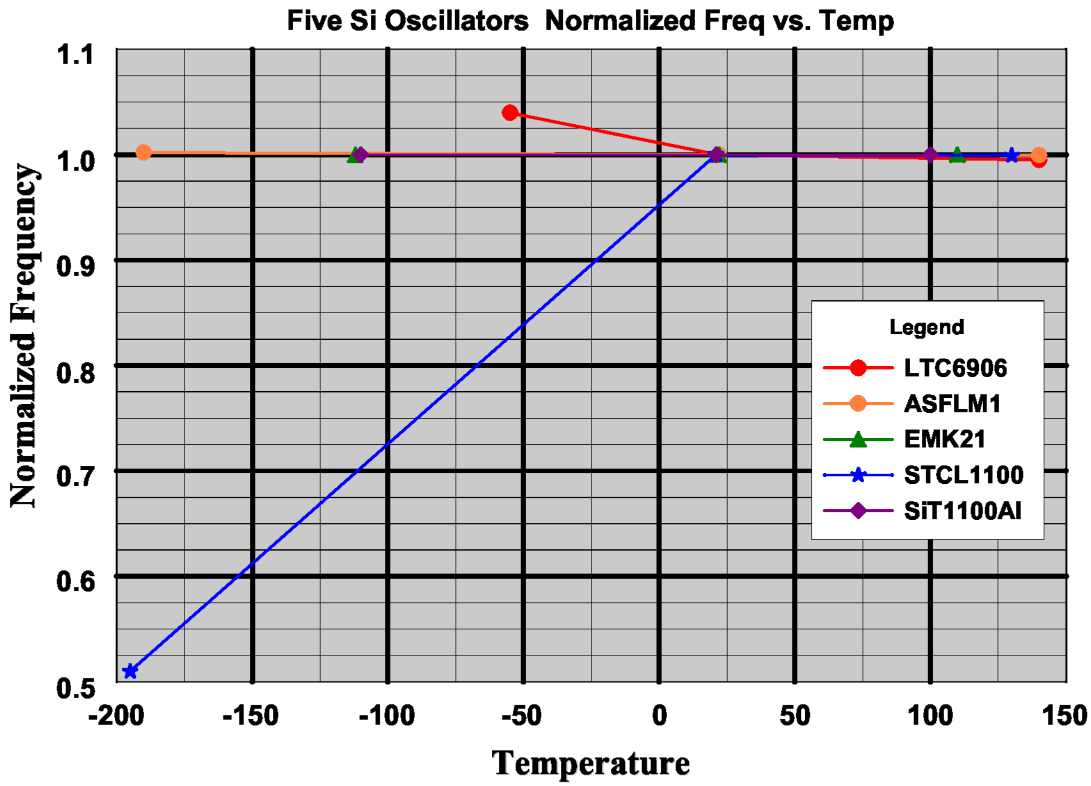


Figure 11. Graph of normalized frequency for the five oscillators covered in this report.

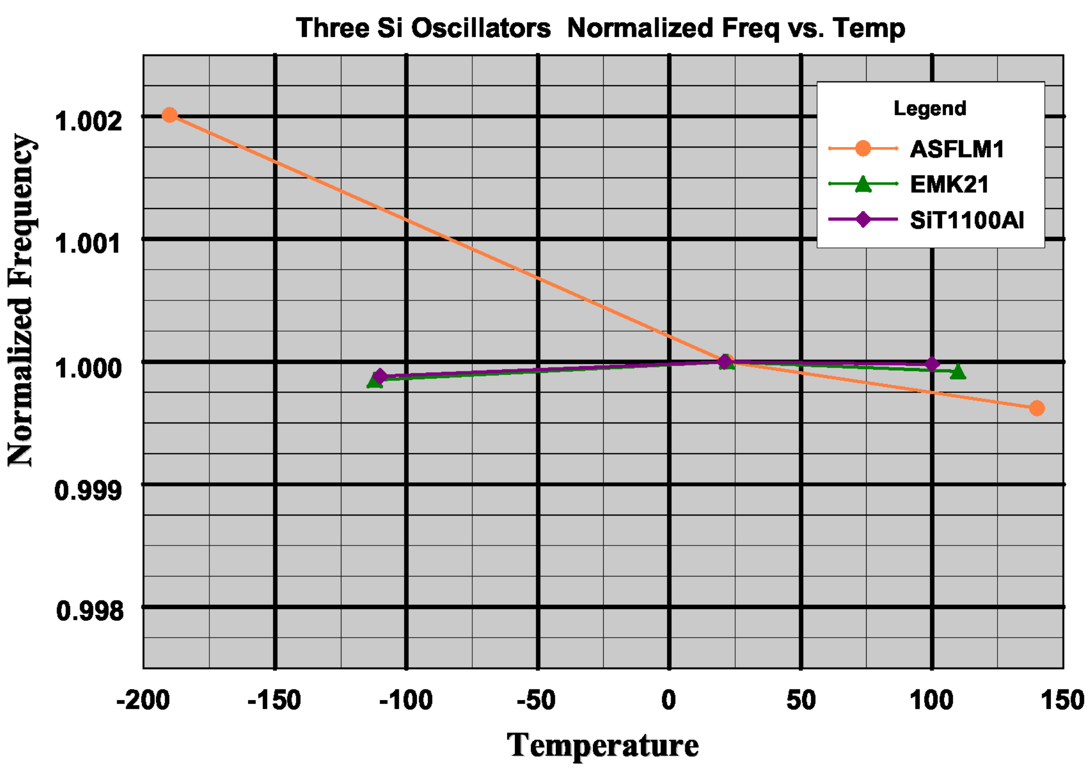


Figure 12. Three most frequency stable SI oscillators vs. temperature.

Conclusions

Silicon oscillators have lately emerged to serve as potential replacement for crystal and ceramic resonators to provide timing and clock signals in electronic systems. These semiconductor-based devices, including those that are based on MEMS technology, are reported to be resistant to vibration and shock (an important criteria for systems to be deployed in space), immune to EMI, consume very low current, require few or no external components, and cover a wide range of frequency for analog and digital circuits.

In this work, the performance of five recently-developed COTS silicon oscillator chips from different manufacturers was determined within a temperature range that extended beyond the individual specified range of operation. In addition, restart capability at extreme temperatures, i.e. power switched on while the device was soaking at extreme (hot or cold) temperature, and the effects of thermal cycling under a wide temperature range on the operation of these silicon oscillators were also investigated. Performance characterization of each oscillator was obtained in terms of its output frequency, duty cycle, rise and fall times, and supply current at specific test temperatures.

The five different oscillators tested operated beyond their specified temperature region, with some displaying excellent stability throughout the whole test temperature range. Others experienced some instability at certain temperature test points as evidenced by fluctuation in the output frequency. Recovery from temperature-induced changes took place when excessive temperatures were removed. It should also be pointed out that all oscillators were able to restart at the extreme test temperatures and to withstand the limited thermal cycling without undergoing any significant changes in their characteristics. In addition, no physical damage was observed in the packaging material of any of these silicon oscillators due to extreme temperature exposure and thermal cycling. It is recommended that additional and more comprehensive testing under long term cycling be carried out to fully establish the reliability of these devices and to determine their suitability for use in space exploration missions under extreme temperature conditions.

References

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Acknowledgments

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