A Voltage-Controlled Oscillator for a 300 MHz High Temperature Transceiver Realized In 0.5μm SOI Technology

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Introduction

The implementation of measurement and monitoring systems for hostile environments poses a significant challenge to system engineers. In many cases, the constraints make traditional measurement techniques impractical or even impossible. Silicon-On-Insulator (SOI) integrated circuit technology offers several distinct advantages which can be leveraged to meet the demands of hostile environments requiring sensors that must be relatively small and be capable of operating over a wide range of temperature.

This paper describes the design and testing of a Voltage-Controlled Oscillator (VCO) designed for a phase-locked loop (PLL) to be used as a frequency synthesizer in a high-temperature sensor system. The scope of this paper is to cover primarily the VCO and it's design, but in order to perform closed-loop testing, a phase detector/charge pump, loop filter, and frequency divider were also designed in SOI. These other circuits will be covered in more detail in the long paper.

Voltage-controlled Oscillator Design and Analysis

The voltage-controlled oscillator accepts a DC control voltage between 0 and 3.3 V and is capable of generating a sinusoidal output signal with a frequency between 250 and 350 MHz. The frequency of the output signal is regulated by the control voltage. Any changes in the control voltage produce a proportional change in the output frequency.

A typical negative-gm L-C oscillator consists of a resonant tank circuit connected to a cross-coupled differential pair of transistors. The transistors act to restore energy that is lost to resistive elements in the tank circuit, where the oscillation takes place. By the nature of the circuit, more energy is restored to the resonator during peaks in the oscillation. This reduces the effects of amplitude noise being translated into phase shifts in the resonant signal, and results in far superior phase noise performance when compared to a ring oscillator [1]. For this reason, the negative-gm L-C oscillator is frequently used in RF applications. Because of its superior phase noise performance and stability, the negative-gm L-C oscillator topology was selected as the basis for the VCO design. The complete VCO design incorporates several features to improve performance and output drive capability. A schematic diagram of the VCO is presented in Figure 1. The varactors and passive components were off chip on the printed circuit board.

Varactor Diodes

Because the varactor diodes directly affect the tuning range and gain of the VCO, their specifications are critical to achieving adequate performance. While most manufacturers' data sheets provide complete characteristics of varactors at room temperature, not many provide the same level of detail at high temperatures. In fact, no manufacturer researched during the VCO design provided any information above 100ºC. This prompted the selection of varactors based on the relative linearity of their performance over a lower temperature range, with the assumption that the linearity would continue over a larger temperature range. As will be shown, this was not completely correct.

Chip Fabrication

The PLLCHIP1 design was fabricated through MOSIS using the Peregrine Semiconductor 0.5μm UTSi SOI process. This is one of several cutting-edge processes that take advantage of the unique electrical properties of silicon deposited on an insulating substrate, also referred to as SOI.

VCO Test Procedures and Results

Testing of the prototype voltage-controlled oscillator was conducted to evaluate several key operating parameters, including tuning range, output drive, and phase noise, and stability of these over temperature. During the tests, the VCO was not connected to the other components of the PLL. This allowed the control voltage to be manually set, and the outputs to be monitored using appropriate test equipment.

Tuning Range

The tuning range of the VCO was characterized by incrementally sweeping the control voltage from rail to rail (0 V to 3.5 V) in steps of 0.25 V. with the output frequency at each step being measured using a spectrum analyzer. In addition, the tuning range tests were conducted over the complete range of operating temperatures, from 25ºC to 200ºC, in increments of 25ºC. The set of curves derived from these tests provided some insight into the gain of the VCO as well as its stability over temperature. Figure 2 shows results of the tuning range tests from one of the two test boards.

These results reveal several important characteristics of the VCO performance. First, the gain remains relatively constant over temperature. The slopes of the control voltage vs. frequency curves do not change significantly over most of the temperature range. However, an interesting anomaly occurred in both test boards at 175 and 200ºC, where an abrupt shift in frequency was observed. This was not predicted by simulations. Because this effect was observed in both test boards at approximately the same temperature and control voltage settings, the anomaly is likely not a function of differences between the test board components or assembly. Instead, it is most likely attributable to a non-linear characteristic of the tank circuit, and most probably, the varactor diodes. Since the manufacturer's measured specifications did not extend above 90ºC, the only means of modeling the diode performance at high temperatures was a continued extrapolation of lower-temperature measurements using the manufacturer's model, which has no means of accounting for discontinuities in the performance of the diode. Therefore, because the varactors control the resonant frequency of the VCO, a reasonable explanation of the discontinuity in the VCO tuning range is a discontinuity in the varactor's reverse-bias capacitance.

Despite these discontinuities, the average gain for both test boards agreed within 5% over all temperatures. The gain drift, or amount of change in gain relative to temperature, agreed within 3% between the test boards. These two results are quite important, as they demonstrate that the VCO has a consistent level of performance between different boards, temperatures, and operating frequencies. Especially notable is the very low gain drift, which averaged approximately 22 kHz/V per ºC. If the anomalies at 175 and 200ºC are excluded, the average gain drift is approximately -3.5 kHz/V per ºC. In either case, the measured gain drift of the VCO demonstrates remarkable stability over temperature, especially considering that many of the components used in the tank circuit had no manufacturer's characterization above 100ºC.

Output Drive

An inspection of the spectrum analyzer plots shows that the output power remains fairly constant over the entire tuning range at a given temperature, with the exception of the anomalies previously discussed at 175 and 200ºC. In those cases, the output power drops abruptly at the point of anomaly, reflecting a drop in the resonant signal voltage in the tank circuit. Like the shift in frequencies, this effect can also be attributed to a discontinuity in the varactors. Overall, the output power levels of the VCO are relatively constant, and are consistent with simulations showing that the output drive of the VCO drops slightly as the ambient temperature increases. The VCO maintained correct operation over a range of supply voltages from 2.55 to 3.3 V, although the output drive was proportionally lower at reduced supply voltages.

Phase Noise

The open-loop phase noise [2] of the VCO was measured using a spectrum analyzer with a resolution bandwidth of 200 Hz. The control voltage was fixed at the midpoint of the tuning range, and data was recorded over the entire range of operating temperatures. A spectral plot over temperature is shown in Figure 3.

The open-loop phase noise performance of the VCO is relatively good, with results over temperature yielding at least -48 dBc at a 10 kHz offset (200 Hz resolution bandwidth) with little variation vs. temperature. This demonstrates that the resonant tank components are capable of maintaining a relatively constant quality factor regardless of temperature. These two characteristics are very important in the overall performance of the PLL. Therefore, good VCO phase noise performance will be reflected in the closed-loop PLL output as well.

Closed-loop Measurements

A block diagram of the PLL is presented in Figure 4. The loop consists of a duty-cycle modulated charge pump, a frequency divider that is binary programmable for a divide ratio between 4 and 512, and the VCO. Both the phase detector/charge pump and divider were fabricated in the same process as the VCO and were on the same chip. For the measurements presented here, the divide ratio was set for 16 (18.75 MHz reference).

The loop worked as expected except for temperatures above 160ºC. The phase noise at 10 KHz offset was approximately the same as that shown in the open loop test and is shown in Figure 5. At approximately 160ºC, the PLL lost phase lock and the output signal immediately jumped to one of the extremes of the VCO tuning range. It appeared the loss of phase lock was due to the output signal of the divider. Due to the small device sizes on the divider output, the divider lacks the ability to fully drive the input of the phase detector at higher temperatures when actually fabricated on the test board with stray capacitance. The PLL system test board is shown in Figure 6.

Summary

A Voltage-Controlled Oscillator (VCO) was designed to operate over a temperature range from 25 to 200ºC. Specific design issues related to the VCO were analyzed and discussed in detail, and test results of prototype circuits were presented. Measurements of the prototyped voltage-controlled oscillator are in agreement with the expected results with the exception of temperatures above 160ºC. The tuning range, output voltage drive and phase noise of the oscillator are all very similar to the results anticipated as a result of hand calculations and computer simulation. In addition, the VCO demonstrated excellent stability over temperature, exhibiting only minimal deviations in operating frequency and phase noise. Results from two independent test boards agreed extremely well, showing consistency across different physical implementations.

References

1. Ali Hajimiri and Thomas H. Lee, "A General Theory of Phase Noise in Electrical Oscillators", IEEE Journal of Solid-State Circuits, Vol. 33, No. 2, February 1998.
2. Thomas H. Lee and Ali Hajimiri, "Oscillator Phase Noise: A Tutorial", IEEE Journal of Solid-State Circuits, Vol. 35, No. 3, March 2000.

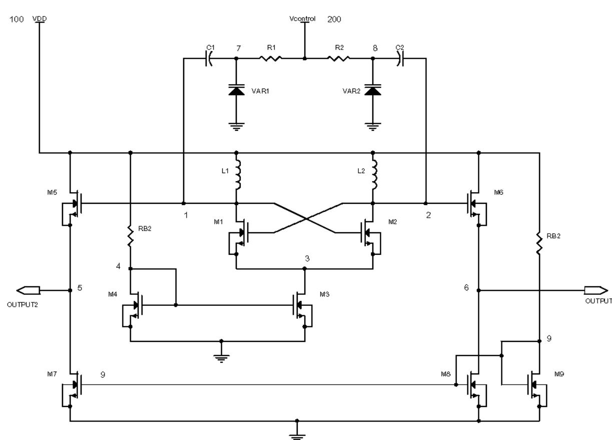

Figure 1. Schematic diagram of the VCO.

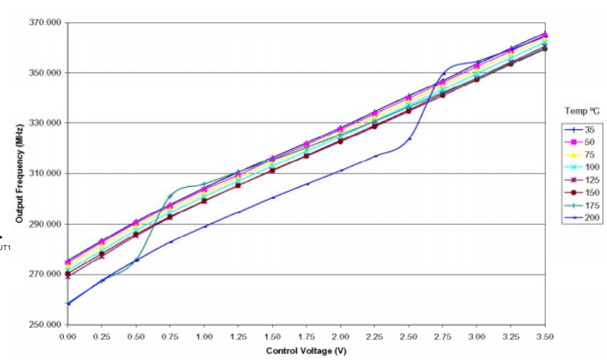

Figure 2. Output frequency vs. control voltage of the VCO.

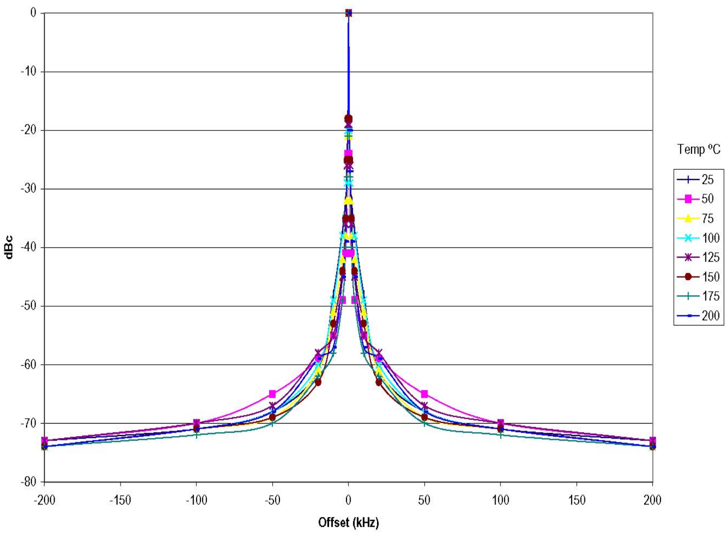

Figure 3. Open -loop phase noise of the VCO.

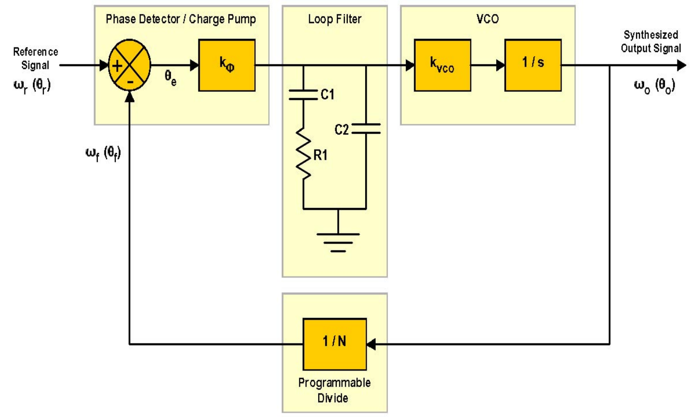

Figure 4. Block diagram of the PLL.

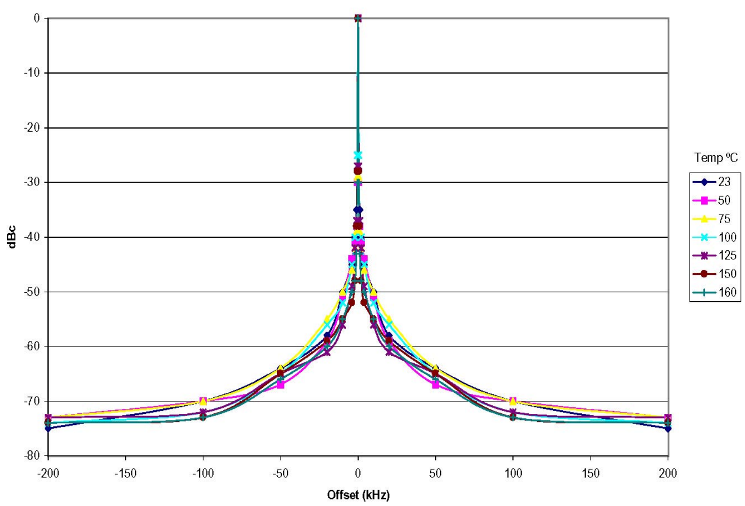

Figure 5. PLL Phase noise vs. Temperature.

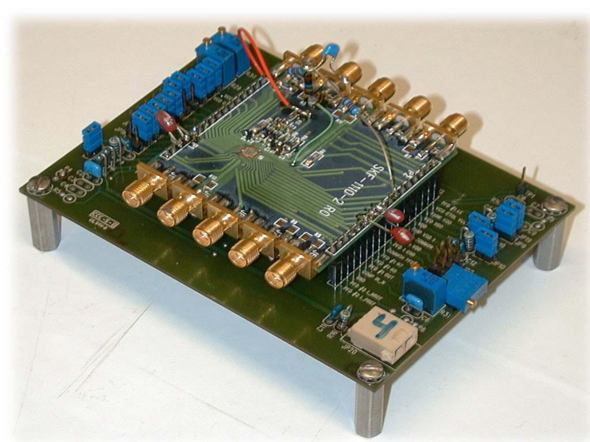

Figure 6. PLL test board.