A High Accuracy and Low Power Temperature Sensor

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Abstract. A resistor-based temperature sensor is designed intended for the temperature compensation of MEMS frequency references. High resolution is then required critically to minimize jitter. A Wien bridge RC filter is used to realize the temperature sensor. When the RC filter is driven at the resonant frequency of the filter, the change of temperature results in phase shift. This phase shift is then digitized by a phase-domain sigma-delta modulator whose phase-summing node is realized by a chopper demodulator. Implemented in a 65nm CMOS technology, the maximum power consumption is only 0.096mW under a supply voltage of 1.2V, and achieves 345 μK/° resolution in a 5 ms conversion time. The sensor occupies an area of 1150μm×650μm. It achieves ±0.035 inaccuracy over the industrial range (-40°C-85°C).

1. Introduction

In recent years, intended to satisfy the temperature compensation of frequency references, integrated temperature sensors are widely researched, which can realize high resolution, high energy efficiency, and high stability at the same time[1,2]. Furthermore, the sensor can be implemented in the CMOS process so that make it can be integrated with the frequency reference’s electronics. In this design, choosing a temperature-sensing resistor which has a large temperature coefficient, low flicker noise and a stable resistance, and using a continuous-time PDΔΣM, with merged chopper to digitized the phase-shift.

In this paper, a high-resolution, energy-efficient temperature sensor uses RC filter implemented in resistors is described. When the filter is driven at the resonant frequency, it displays a phase shift, which is associated with the change of temperature. Since the capacitors are extremely stable, the phase shift will depend mainly on the resistor’s temperature coefficient. This phase shift is digitized by an analog to digital converter based on a continuous-time phase-domain delta-sigma modulator[3]. In order to meet the require of temperature compensation of frequency references, the accuracy of the sensor should higher than 0.1°C, and the SNR (Signal-to-Noise Ratio) of the a phase-domain sigma-delta modulator should higher than 80dB and achieved 83.1dB in this design.

2. System Design

Two signals are required to measure temperature: a signal is associated with temperature and a reference signal. The resistors can be used in the CMOS process, and all behave temperature coefficients (1000s of ppm/℃) that cannot be ignored. A method of engendering a temperature dependent signal is by applying the phase-shift of an RC filter, which depends on its driven frequency and on the value of its resistors and capacitors. Low-pass and band-pass filters are appropriate, because they all impose bandwidth limitations on the thermal noise of the resistor at high frequencies. Figure 1 illustrates two possible circuit configurations: a low-pass and a band-pass filter. Their amplitude transfer functions and phase transfer functions are given as follows:

Low pass filter:
\[ H(jw) = \frac{1}{1 + RCjw} \]  
(1)

\[ \varphi_{RC-LP}(jw) = -\tan^{-1} RCw \]  
(2)

Wien bridge band pass filter:

\[ H(jw) = \frac{RCjw}{(1 - R^2C^2w^2) + 3RCjw} \]  
(3)

\[ \varphi_{RC-WB} = -\tan^{-1} \left( \frac{R^2C^2w^2 - 1}{3RCw} \right) \]  
(4)

Figure 1. low pass filter(left) and Wien bridge band pass filter (right).

Figure 2. Bode plots of the low pass and Wien Bridge filters.

Figure 3. The phase shift of Wien bridge and low-pass.
Figure 4. Systematic phase shift nonlinearity error.

The relevant Bode plots are illustrated in Figure 2. The driving frequency $\omega = 1/RC$ is cut-off frequency of the low pass filter, and is center frequency of the Wien bridge. Figure 3 demonstrates that the phase shift with temperature can be approximated as a linear relationship, and the temperature range is -40°C to 85°C, $R = R_0(1 + \alpha (T - T_0))$ with temperature coefficient is $\alpha$ (0.14%) and driving frequency is $f_0$ (500 kHz). The non-linearity error of these filters is illustrated in Figure 4. Obviously, the nonlinearity of the low-pass filter is 0.14°C, which goes beyond the 0.1°C target, and the error of Wien bridge filter is 0.035°C. Therefore, choosing the Wien bridge filter rather than the more concise low-pass filter. From Figure 3, it can be seen that over the industrial temperature range, the total phase-shift of the Wien bridge is only about 11, and so needing a precision phase process circuit. A phase-domain sigma-delta modulator (PDΣΔM) can well achieve this target[4,5].

A phase-domain ΣΔM uses a sampling frequency much larger than the Nyquist frequency of the signal being converted, which can reduce the amplitude of the floor noise in useful bandwidth. By shaping quantization noise power spectral density, the error in the quantization can be filtered. The first step in the design of a phase-domain ΣΔM is high-level design and simulation to synthesis suitable NTF (Noise Transfer Function), the block diagram of the phase-domain ΣΔM is shown in Figure 5, which is designed in matlab/simulink.

Figure 5: Behavioral simulation of phase domain sigma-delta modulator

3. Architecture and Circuit Implementation

The block diagram of the proposed temperature sensor is shown in Figure 6. The driving signals, $\phi_{\text{drive+}}$ and $\phi_{\text{drive-}}$, at $f_{\text{drive}} = 500kHz$, In order to achieve high resolution, a continuous-time PДΣМ is applied to digitize the phase $\phi_{\text{WB}}(T)$ of the WB’s output current.
The PDΔΣM by multiplying input signal and a phase reference at the same frequency (f_{demod} = f_{drive}) to converts $\varphi_{WB}(T)$ to dc. The output of the multiplier depends on the feedback phase of the phase digital-to-analog converter, and the demodulated DC output is positive or negative. The loop filter integrates the output of the multiplier and quantizes it by a quantizer. The value of the output bit stream is representing a digital result of $\varphi_{WB}(T)$.

The first stage integrator uses a two-stage operational amplifier, and the first stage of the op amp does not need to provide an output current. Therefore, a large input swing is not required, and the temperature sensing error is reduced. In this design, the first stage integrator is implemented in a two-stage opamp as shown in Figure 7. The two PMOS transistors working in the triode area are used as the common mode feedback of the first stage of the op amp. The 500 kHz chopping effectively eliminates the flicker noise of the op amp with a corner frequency of approximately 14 kHz. In order to reduce the output swing of the first stage, which simplifies the design of the gm-C stage, the integration capacitance of the first stage is very large.

4. **Layout and Simulation**

The sensor is fabricated in a standard 65nm CMOS technology, and the layout of the temperature sensor is shown in Figure 8.

Figure 9 presents the power spectral density of the output bit stream. The noise floor of the sensor is mainly the thermal noise of the RC filter. The SNR is 83.1dB, and according to SNR=6.02N+1.76, the...
effective number of bits is 13. According to the fig.4, the sensor achieves an inaccuracy of 0.035°C.

Figure 9. Power spectral density of the output bit stream.

5. Conclusion
A resistor-based temperature sensor has been implemented in a standard 65nm CMOS technology. It uses a resistor in the WB RC filter for temperature sensing, and its output temperature-dependent phase signal is digitized by continuous time PΔΣM. Mainly due to the high TC and low noise of resistors, the sensor achieves an inaccuracy of ±0.2 °C from −40 °C to 85 °C. After a first order fit and a systematic nonlinearity correction, this can be reduced to ±0.03 °C. It can be seen from the results that the rc filter can be used as a temperature sensing module for precise frequency reference temperature compensation.

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