Current-Ratio Temperature Compensation in Bipolar Relaxation Oscillators

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Abstract

A new temperature compensation strategy for bipolar relaxation oscillators is presented. The compensation scheme is suitable for both Schmitt-trigger oscillators and emitter-coupled multivibrators and requires a minimum amount of circuitry for the compensation. The feasibility of this compensation scheme is demonstrated by the results of a test chip. Without any trimming and with a total current consumption of 2.5mA, a temperature coefficient of approximately -90ppm/°C has been achieved at frequencies up to 2.5MHz.

1. Introduction

Bipolar relaxation oscillators are frequently used in monolithic voltage controlled oscillator designs. These oscillators display excellent control linearity, though temperature compensation has always been an important issue. Among the bipolar relaxation oscillators, two major subclasses can be distinguished, which are formed by Schmitt-trigger oscillators and multivibrators. Various temperature compensation techniques have been reported [1],[2], though these schemes always focus on either Schmitt-trigger oscillators or multivibrators.

The current-ratio temperature compensation strategy, which will be presented in this paper, offers good perspectives for both Schmitt-trigger oscillators and multivibrators. The key in the approach is the fact that the currents in all branches of the oscillator core are defined by the circuit topology only. Utilising translinear loops, the hysteresis voltage is then defined by a precise reference voltage, thereby eliminating the fundamental origin of temperature dependence.

2. Temperature compensation in Schmitt-trigger oscillators

2.1. Schmitt-trigger oscillators

A well-known bipolar Schmitt-trigger oscillator is depicted in Figure 1. Its operation is briefly explained as follows. At any time, either T_1 or T_2 is conducting, causing the output voltage across the resistor R_1 to be either low or high. This output voltage controls a current switch such that the timing capacitor C is either charged or discharged, resulting in a triangular voltage waveform across the timing capacitor. Due to the positive feedback, the Schmitt-trigger circuit will remain in a stable state until a critical voltage level at the trigger input is reached, at which time the circuit will change state. Subsequently, the current switch will be operated, such that the timing capacitor will be alternately charged and discharged by a current I_C, the frequency of oscillation being defined by the control current I_C, the capacitor C and the hysteresis voltage of the Schmitt-trigger.

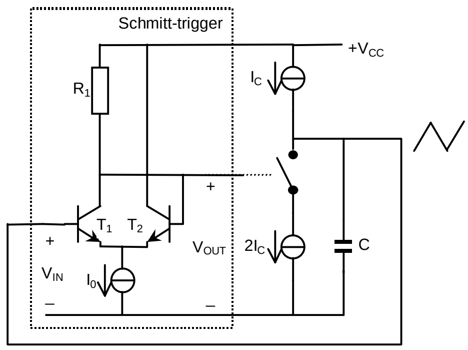

Figure 1. Basic Schmitt-trigger oscillator

The hysteresis voltage of the bipolar Schmitt-trigger strongly depends on temperature [1], which implies that the frequency of oscillation has to be compensated for temperature dependence.

2.2. The current-ratio Schmitt-trigger

The current-ratio Schmitt-trigger [3] is based upon the basic bipolar Schmitt-trigger and is shown in Figure 2. In this circuit, temperature compensation of the hysteresis voltage is achieved by an adaptation of the circuit topology. T_1 and T_2 can be recognised to be a differential pair with unity gain positive feedback. The resistive collector load of the bipolar Schmitt-trigger has been replaced by a V_{LO}-cell, composed of T_5 through T_8, and a V_{HI}-cell, which consists of T_3 and T_4.

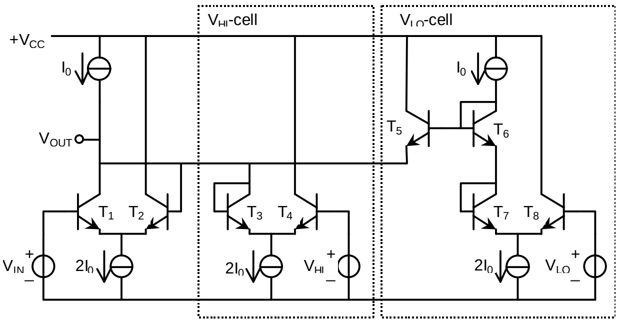

Figure 2. The current-ratio Schmitt-trigger

The circuit operation will now be explained. First, suppose that V_{OUT} is high. Since transistor T_5 is off, the collector load of transistor T_1 equals the small signal impedance of the V_{HI}-cell.

$$Z_{HI} = r_{e3} + r_{e4} \tag{1}$$

Assume that T_1 carries a current $(1-\lambda)I_0$. Then, I_{C2}, I_{C3} and I_{C4} can also be expressed in terms of I_0 and λ:

$$\begin{aligned} I_{C1} &= (1-\lambda)\cdot I_0 \qquad I_{C2} = (1+\lambda)\cdot I_0 \\ I_{C3} &= \lambda \cdot I_0 \qquad I_{C4} = (2-\lambda)\cdot I_0 \end{aligned} \tag{2}$$

The regeneration process will start when the loop gain reaches unity. This occurs when the collector load resistance equals the sum of the emitter load resistances:

$$r_{e1} + r_{e2} = r_{e3} + r_{e4} \tag{3}$$

Assuming equal junction temperatures for all transistors, substitution of the collector currents and solving for the current ratio λ yields:

$$\frac{1}{1-\lambda} + \frac{1}{1+\lambda} = \frac{1}{\lambda} + \frac{1}{2-\lambda} \quad \Rightarrow \quad \lambda = \lambda_{HI} = \frac{1}{2} \tag{4}$$

After the Schmitt-trigger has changed state, the collector load of T_1 equals the small signal impedance of the V_{LO}-cell. Now, regenerative switching will occur when:

$$r_{e1} + r_{e2} = r_{e5} \tag{5}$$

Continuing the calculation yields the current ratio at the lower switching instant: $\lambda_{LO} = -1+\sqrt{2}$.

Summarising: the current ratios at the regeneration instant are uniquely defined by the circuit topology and independent of temperature or the absolute values of the collector currents.

Now, let us take a closer look at the circuit when the input voltage V_{IN} approaches V_{HI}. A translinear loop can be recognised from V_{IN} to V_{HI}.

$$V_{IN} - V_{BE1} + V_{BE2} - V_{BE3} + V_{BE4} = V_{HI} \tag{6}$$

These base-emitter voltages can be expressed in the collector currents that have been obtained recently:

$$V_{IN} + \frac{k \cdot T}{q} \ln \frac{I_{C2} \cdot I_{C4} \cdot I_{CS1} \cdot I_{CS3}}{I_{CS2} \cdot I_{CS4} \cdot I_{C1} \cdot I_{C3}} = V_{HI} \tag{7}$$

$$V_{IN} + \frac{k \cdot T}{q} \ln \frac{(1+\lambda_{HI}) \cdot (2-\lambda_{HI})}{\lambda_{HI} \cdot (1-\lambda_{HI})} - \frac{k \cdot T}{q} \ln \frac{I_{CS2} \cdot I_{CS4}}{I_{CS1} \cdot I_{CS3}} = V_{HI} \tag{8}$$

In these equations, I_{CS} represents the saturation current of a transistor, which is proportional to the effective emitter area of that transistor. This implies that the Schmitt-trigger thresholds can be made independent of temperature by properly scaling one of the emitter areas in the translinear loop. Substitution of the current-ratio λ_{HI} in Equation 8 yields that multiplying the emitter area of T_4 by 9 will make the temperature-dependent terms zero.

Similarly, a second translinear loop is provided by the V_{LO}-cell when the circuit is in the other relaxation state. Now, substitution of $\lambda_{LO} = -1+\sqrt{2}$ yields that the emitter area of T_5 has to be multiplied by 5.82. The threshold levels of the current ratio Schmitt-trigger are now defined by reference voltages V_{LO} and V_{HI}. Oscillators using this new Schmitt-trigger will therefore not require additional temperature compensation.

3. Temperature compensation in multivibrators

3.1 Multivibrators

The emitter-coupled multivibrator is another commonly used oscillator implementation, which is often preferred over a Schmitt-trigger oscillator [2].

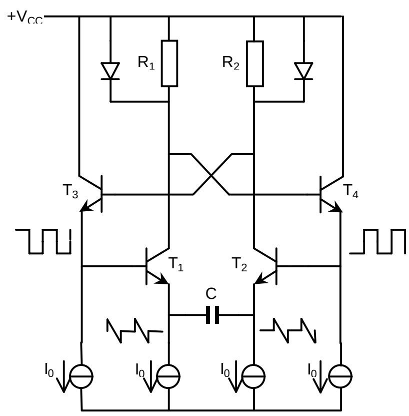

Figure 3. Basic emitter-coupled multivibrator

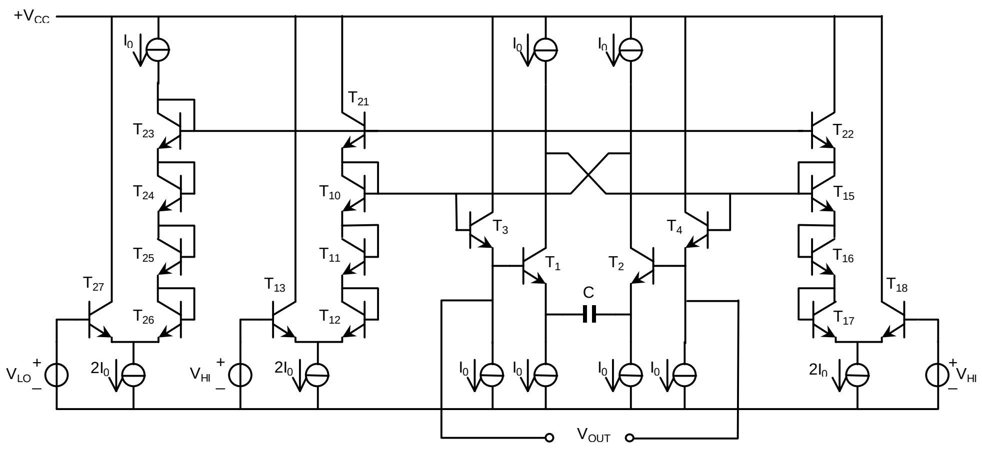

Figure 4. Simplified schematic of the current-ratio multivibrator

A brief explanation of the circuit operation is merited. The circuit is comprised of two cross-coupled gain stages, which assures that at any moment, either transistor T_1 or T_2 is on, such that the capacitor is alternately charged and discharged with equal but opposite currents.

Due to the charging of the capacitor, the base-emitter voltage of the non-conducting transistor is increasing until the loopgain reaches unity. At that moment, the circuit changes state and the cycle repeats. The voltage across the capacitor at the regeneration instant equals one diode voltage drop, which is defined by the collector clamping diodes. The frequency of oscillation therefore exhibits strong temperature dependence.

3.2 The current-ratio multivibrator

A temperature independent capacitor voltage at the regeneration instant is what is needed to assure temperature independent operation. In order to define the capacitor voltage at the switching instant, modified versions of the V_{HI}-cell and the V_{LO}-cell, which have been introduced in the current-ratio Schmitt-trigger circuit, are utilised. The simplified schematic has been given in Figure 4. Like in the basic multivibrator, the heart of the oscillator is composed of two cross-coupled gain stages, formed by T_1 and T_2, along with a floating timing capacitor between their emitters. T_3 and T_4 are emitter-followers that provide the voltage level shift needed to keep T_1 and T_2 from saturation. Two V_{HI}-cells are comprised of transistors T_{10} through T_{13} and transistors T_{15} through T_{18} respectively. The V_{LO}-cells consist of transistors T_{21} and T_{22} together with a common part formed by transistor T_{23} through T_{27}.

Like in the current-ratio Schmitt-trigger, the currents in the multivibrator core are uniquely defined at the regeneration instant thanks to the circuit topology. These currents can be expressed in terms of I_0 and the current ratio λ. Assume that the collector of T_2 is low.

$$I_{C1} = (1-\lambda)\cdot I_0 \qquad I_{C2} = (1+\lambda)\cdot I_0$$
$$I_{C10} = I_{C11} = I_{C12} = \lambda\cdot I_0 \qquad I_{C13} = (2-\lambda)\cdot I_0$$
$$I_{C22} = \lambda\cdot I_0 \tag{9}$$

Regenerative switching takes place when:

$$r_{e1} + r_{e2} = Z_{HI} + Z_{LO} = 3\cdot r_{e10} + r_{e13} + r_{e22} \tag{10}$$

Substitution of these equations yields the current-ratio:

$$\frac{1}{1-\lambda} + \frac{1}{1+\lambda} = \frac{3}{\lambda} + \frac{1}{2-\lambda} + \frac{1}{\lambda} \quad \Rightarrow \quad \lambda = 0.8089 \tag{11}$$

Again, translinear loops from the reference voltages to either side of the timing capacitor are achieved by scaling of effective emitter areas:

$$V_{E1} = V_{HI} + \frac{k\cdot T}{q}\cdot \ln\frac{\lambda^3}{(1+\lambda)\cdot(2-\lambda)}\cdot\frac{I_{CS13}}{I_{CS}}$$
$$V_{E2} = V_{LO} + \frac{k\cdot T}{q}\cdot \ln\frac{\lambda}{(1-\lambda)\cdot\lambda}\cdot\frac{I_{CS26}}{I_{CS}} \tag{12}$$

Substitution of the current-ratio yields that accurate temperature compensation is achieved when the emitter areas of T_{13} and T_{18} are multiplied by 4.07, and the area of T_{26} is multiplied by 6.47.

4. Circuit simulations

Computer simulations have been done to investigate the effects of non-ideal transistor behaviour. Switching delays turned out to be the most important source of the remaining temperature dependence and non-linearity, particularly at frequencies where these delays formed a considerable contribution to the oscillation period. Thanks to the tighter coupling within the regenerative loop, the multivibrator performed better than the current-ratio Schmitt-trigger oscillator with respect to linearity and temperature dependence.

Calculation of the temperature coefficient of the simplified current-ratio multivibrator yields the results shown in Figure 5. In this calculation, frequency has been varied by the control current for three different values of the timing capacitance, whereas the hysteresis voltage equals 500mV.

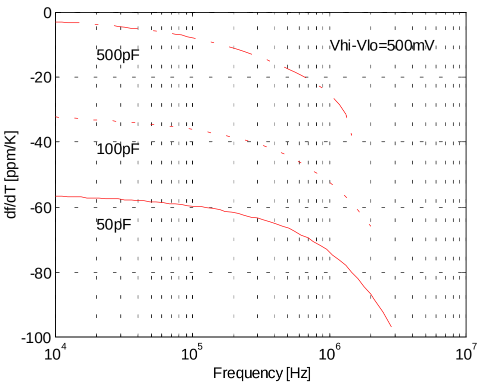

Figure 5. Calculated temperature coefficient as a function of control current

Figure 5 shows that the temperature coefficient varies little over a wide frequency range even for small timing capacitors and hence small currents. This implies that, once the hysteresis voltage is known, trimming of the remaining temperature coefficient can be achieved by intentionally introducing an additional emitter-area mismatch in one of the translinear loops.

5. Circuit realisation and measurements

The presented current-ratio multivibrator circuit has been fabricated on a 2.5GHz, 2µm bipolar/CMOS process to verify the feasibility of the presented temperature compensation strategy.

Spreading analyses have shown that thermal gradients and emitter area mismatches between the transistors in the multivibrator core are the main contributions to spreading in the temperature coefficient. Spreading can be minimised by careful layout of the multivibrator core and by avoiding minimum size transistors in the translinear loops. Though it has not been verified experimentally, calculations [3] have indicated that the standard deviation of the spreading can be kept below 10ppm/°C at a hysteresis voltage of 500mV.

A photograph of the realised multivibrator is shown in Figure 7. The large devices at the top form a 50pF internal timing capacitor. The multivibrator core has been placed in the centre of the chip. For modelling reasons, the scaled emitter areas have been realised by placing the required number of transistors in parallel. Though only integer ratios are available in this way, calculations have shown that the introduced temperature dependence due to this error is small.

Measurements have been performed on the current-ratio multivibrator with a 50pF on-chip timing capacitor and an externally applied hysteresis voltage of 500mV. Frequency has been varied by the control current at different junction temperatures. Some results have been given in Figure 6. Due to the limited accuracy of the current measurement equipment, the results show some scattering. Nevertheless, the results seem to be accordance to the simulations.

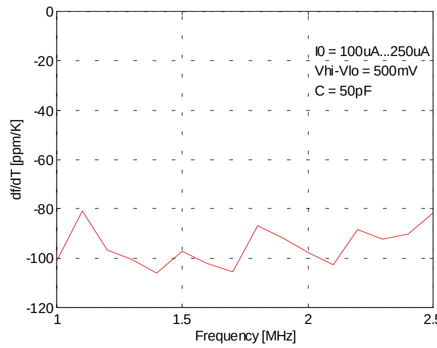

Figure 6. Measured temperature coefficient

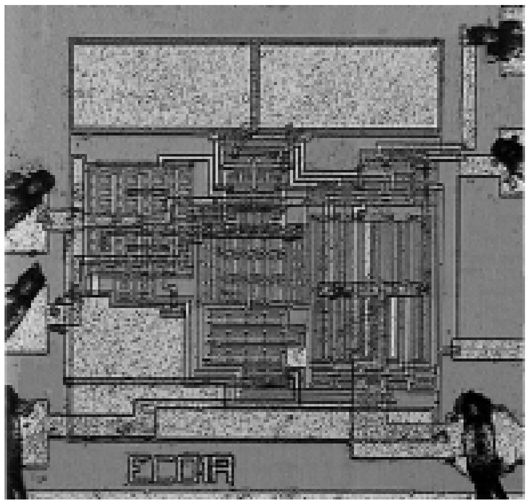

Figure 7. Photograph of the multivibrator

6. References

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