# A Wide-Tunable Translinear Second-Order Oscillator

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**Abstract**

This paper describes the design and measurement of a translinear second-order oscillator. The circuit is a direct implementation of a nonlinear second-order differential equation and follows from a recently developed synthesis method for dynamic translinear circuits. It comprises only two capacitors and a handful of bipolar transistors and can be instantaneously controlled over a very wide frequency range by only one control current, which indicates its suitability for spread-spectrum communications. Its total harmonic distortion can be made small by design, which enables fully integrated transmitters. A semicustom test chip, fabricated in a standard 2-$\mu$, 7-GHz, bipolar IC process, operates from a single supply voltage, which can be as low as 2 V and oscillates over 6 decades of frequency with -31 dB total harmonic distortion.

## 1 Introduction

Recently, both an analysis method and a synthesis method for dynamic translinear circuits were proposed by the authors [1, 2]. The dynamic translinear principle can be regarded as a generalization of the well-known 'static' translinear principle, formulated by Gilbert in 1975 [3]. By using the dynamic translinear principle, it is possible to implement every linear or nonlinear differential equation, using transistors and capacitors only. See, e.g., [4, 5].

Here, we present the design and experimental results of a wide-tunable translinear second-order oscillator. The circuit, which comprises only two capacitors and a handful of transistors, is a direct implementation of a nonlinear second-order differential equation by means of the synthesis method proposed in [2] and is tuned by only one control current. To the authors' knowledge, this is the first time a translinear oscillator has actually been implemented.

The organization of the paper is as follows. Section 2 introduces the dynamic translinear principle, which subsequently is elaborated into the design of a second-order oscillator in Section 3, following a systematic approach. The experimental results of a semicustom implementation of the translinear oscillator are discussed in Section 4. Finally, Section 5 deals with the conclusions.

## 2 Dynamic translinear principle

The key to the dynamic translinear principle, from a current-mode point of view, are the capacitance currents. We therefore concentrate on the simple substructure, depicted in Figure 1. Assuming a bipolar transistor, it follows [1]: $CV_T\dot{I}_C = I_C I_{\text{cap}}$, $C$, $V_T$, $I_C$ and $I_{\text{cap}}$ being the capacitance value, the thermal voltage $kT/q$, the collector current and the capacitance current, respectively. The dot represents differentiation with respect to time.

From this equation, it can be seen that a time derivative in a differential equation can be replaced by a product of two currents. This product of currents can be elegantly realized by means of the translinear principle [3].

# 3 Oscillator design

The design of a second-order dynamic translinear oscillator starts with a dimensionless differential equation that describes the oscillator behavior in the time domain:

$$\frac{d^2x}{d\tau^2} + wf(x)\frac{dx}{d\tau} + w^2x = 0 \quad (1)$$

This equation describes the oscillator signal $x$ as a function of a control signal $w$. $f(x)$ is an arbitrary (nonlinear) even-symmetry function of $x$. When $f(x) > 0$, the oscillator is damped and the amplitude decreases. When $f(x) < 0$, the oscillator is undamped and the amplitude increases. $\tau$ is the dimensionless time of the oscillator.

## 3.1 Transformations

The first synthesis step is the transformation of the above differential equation such that the dimensions of the resulting equation are suitable for a translinear realization. In dynamic translinear circuits, all signals are currents. Hence, the signals $w$ and $x$ can be transformed into the currents $I_F$ and $I_{\rm osc}$ through the equations: $w = I_F/I_O$ and $x = I_{\rm osc}/I_O$, $I_O$ being a DC bias current that determines the absolute current swings.

The dimensionless time $\tau$ can be transformed into the time $t$ with dimension $[s]$ through the equation [2]: $d/d\tau = CV_T/I_O \cdot d/dt$. Applying the above transformations, the resulting differential equation becomes: $C^2V_T^2\ddot{I}_{\rm osc} + CV_TI_Ff(I_{\rm osc}, I_F)\dot{I}_{\rm osc} + I_F^2I_{\rm osc} = 0$.

## 3.2 Definition of the capacitance currents

The next synthesis step is the elimination of the derivatives. In the previous section, we saw that a derivative can be replaced by a product of a capacitance current and a collector current. The capacitor currents can be introduced one by one. Each capacitance current reduces the order of a differential equation by one, until finally a current-mode multivariant polynomial results.

Using $\dot{F}(I_{\rm osc}, I_F) = f(I_{\rm osc}, I_F)\dot{I}_{\rm osc}$ and defining $I_{\rm cap1}$ and $I_{\rm cap2}$ as $I_{\rm cap1} = CV_T\dot{I}_{\rm osc}/(I_{\rm osc} + I_F)$, $I_{\rm cap2} = CV_T\dot{I}_Q/(I_Q + I_F)$ and $I_Q = I_{\rm osc} - I_{\rm cap1} - F(I_{\rm osc}, I_F) - I_{\rm osc}I_{\rm cap1}/I_F$, the above differential equation transforms into:

$$F()I_{\rm cap2}I_F + I_{\rm cap1}(I_{\rm cap2} + I_F)(I_F + I_{\rm osc}) - I_F(I_{\rm cap2}(I_F + I_{\rm osc}) - I_FI_{\rm osc}) = 0 \quad (2)$$

## 3.3 Translinear decomposition

The above polynomial is the basis of the next synthesis step, which is translinear decomposition. That is, the polynomial has to be mapped onto a set of translinear loop equations that are each characterized by the general equation: $\prod_{\rm CW} J_{C,i} = \prod_{\rm CCW} J_{C,i}$, $J_{C,i}$ being the transistor collector current densities in clockwise (CW) or counter-clockwise (CCW) direction. To this end, the synthesis methods for static translinear circuits expounded in [6] can be used. One possible solution is achieved by 'parametric' decomposition of Equation (2). Two intermediate currents, $I_P$ and $I_Q$, are introduced, resulting in:

$$(I_F + I_P - I_Q)I_F = (I_F + I_{\rm cap1})(I_{\rm osc} + I_F) \quad (3)$$

$$(I_F + I_P)I_F = (I_F + I_{\rm cap2})(I_Q + I_F) \quad (4)$$

$$I_P = 2I_{\rm osc} - F(I_{\rm osc}, I_F) \quad (5)$$

From its definition, it follows that $F(I_{\rm osc}, I_F)$ must be a nonlinear time-invariant odd-symmetry function of $I_{\rm osc}$ and $I_F$, whose derivative $f(I_{\rm osc}, I_F)$ with respect to $I_{\rm osc}$ is negative for small values of $I_{\rm osc}$ and positive for large values of $I_{\rm osc}$. A suitable choice is: $F(I_{\rm osc}, I_F) = 2I_{\rm osc} - \frac{2GI_{\rm osc}I_F^2}{I_{\rm osc}^2 + I_F^2}$, $G$ being a constant, which must be larger than one. This function is easily implemented in a translinear circuit using the generic principle described in [7].

## 3.4 Biasing

The final synthesis step is biasing. In other words, the translinear decomposition that was found during the previous synthesis step has to be mapped onto a correct translinear circuit topology and the correct currents must be supplied to this topology.

A possible biasing arrangement for the translinear oscillator is depicted in Figure 2. Transistors $QN1$ through $QN4$ and $QN11$ through $QN14$ implement Equations (4) and (3), respectively. $QN31$ delivers the oscillator output current $I_{\rm osc}$. $QN8$, $QN9$, $QN18$, $QN19$, $QN28$ and $QN47$ compensate for the Early effect. A PNP current mirror with multiple outputs (transistors $QP41$ through $QP48$) produces replicas of $I_F$. $QP40$ enlarges the loop gain, thereby reducing the influence of the base currents. The constant factor $G$ is set by the ratio of the emitter areas of $QN48$ and $QN46$.

## 4 Experimental results

To verify the circuit operation in practice, the active circuitry of the oscillator was integrated onto a semicustom version of our in-house 2-$\mu$ bipolar IC process. Typical transistor parameters are: $h_{\mathrm{fe,NPN}} \approx 100$, $f_{T,\mathrm{NPN}} \approx 7$ GHz, $h_{\mathrm{fe,LPNP}} \approx 80$ and $f_{T,\mathrm{LPNP}} \approx 40$ MHz. $G$ equals 5/4 by design.

Experiments proved the correct operation of the translinear oscillator for supply voltages from 5 V down to 2 V. The current consumption approximately equals 18 times $I_F$. Figure 3 depicts the oscillation frequency $f_{\mathrm{osc}}$ (in Hz) as a function of control current $I_F$ for four different capacitor values, all easily integratable: 560 pF, 56 pF, 15 pF and the 'intrinsic' capacitance, stemming from a bond flap, a bond wire and a pin. From this plot, it can be deduced that this particular translinear oscillator can be controlled over a very wide frequency range of 6 (!) decades. Oscillations higher than half the $f_{T,\mathrm{LPNP}}$ were measured.

The favorable property of a very wide frequency range makes the translinear oscillator an interesting candidate for frequency synthesizers, such as those needed in, e.g., spread-spectrum receivers and transmitters.

Since $F$ is a time-invariant function of $I_F$ and $I_{\mathrm{osc}}$, the output current waveform is independent of the oscillation frequency. This has been verified by means of a dynamic signal analyzer and proved to be true for the complete 'linear' current range, i.e., between 2 nA and 200 $\mu$A. Figure 4 depicts the output frequency spectrum of the oscillator running at 1.7 MHz. The supply voltage and the current consumption equal 3 V and 2.8 mA, respectively. Both capacitors equal 560 pF. The total harmonic distortion is mainly determined by the second and the third harmonic and equals 2.7 % or -31 dB.

The small harmonic distortion feasible with translinear oscillators makes them especially interesting for the development of fully integrated transmitters, since bulky and expensive off-chip filtering may be no longer necessary.

At 20 kHz offset from the carrier frequency, the phase noise equals -99 dBc/Hz, which is reasonable for an oscillator with such a wide tuning range. Since the dominant noise sources in translinear oscillators, as in all (dynamic) translinear circuits, i.e., the collector shot noise sources, are proportional to the collector currents, a better noise performance may be obtained at the expense of a larger control current $I_F$ and, for the same oscillation frequency, two larger capacitors.

## 5 Conclusions

A translinear second-order oscillator has been introduced. The circuit is a direct implementation of a nonlinear second-order differential equation. It comprises only two capacitors and handful of transistors and can be instantaneously controlled over a very wide frequency range by only one control current ($I_F$), which indicates that the translinear oscillator is an interesting candidate for spread-spectrum frequency synthesizers. Its harmonic distortion is directly related to another parameter ($G$) and can be made small by design, thereby paving the way to fully integrated transmitters.

A semicustom version of the proposed circuit operates from a single supply voltage down to 2 V, oscillates over 6 decades of frequency with -31 dB total harmonic distortion. Oscillation frequencies up to half the $f_{T,\mathrm{LPNP}}$ were measured. At 1.7 MHz, using two 560 pF capacitors, the current consumption equals 2.8 mA, and the phase noise equals -99 dBc/Hz at a 20 kHz offset from the oscillation frequency.

## References


[1] J. Mulder, A.C. van der Woerd, W.A. Serdijn and A.H.M. van Roermund: "General current-mode analysis of translinear filters," IEEE Transactions on Circuits and Systems, March 1997.

[2] J. Mulder, W.A. Serdijn, A.C. van der Woerd and A.H.M. van Roermund: "Current-mode synthesis of dynamic translinear circuits," to appear.

[3] B. Gilbert: "Translinear circuits: a proposed classification," Electronics Letters, Vol. 11, No. 1, January 1975, pp. 14-16.

[4] J. Mulder, A.C. van der Woerd, W.A. Serdijn and A.H.M. van Roermund: "An RMS-DC converter based on the dynamical translinear principle," Proc. ESSCIRC'96, Neuchatel, Switzerland, 1996.

[5] W.A. Serdijn, M. Broest, J. Mulder, A.C. van der Woerd and A.H.M. van Roermund: "A low-voltage ultra-low-power translinear integrator for audio filter applications," IEEE Journal of Solid-State Circuits, April 1997.

[6] E. Seevinck: "Analysis and synthesis of translinear integrated circuits," Elsevier, Amsterdam, 1988.

[7] B. Gilbert: "Current-mode circuits from a translinear viewpoint: a tutorial," in: C. Toumazou, F.J. Lidgey and D.G. Haigh (editors): Analogue IC design: the current-mode approach, Peter Peregrinus, London, 1990.

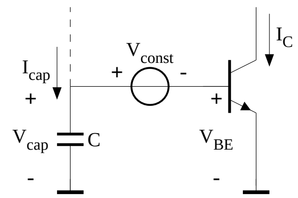


Figure 1: Principle of dynamic translinear circuits.

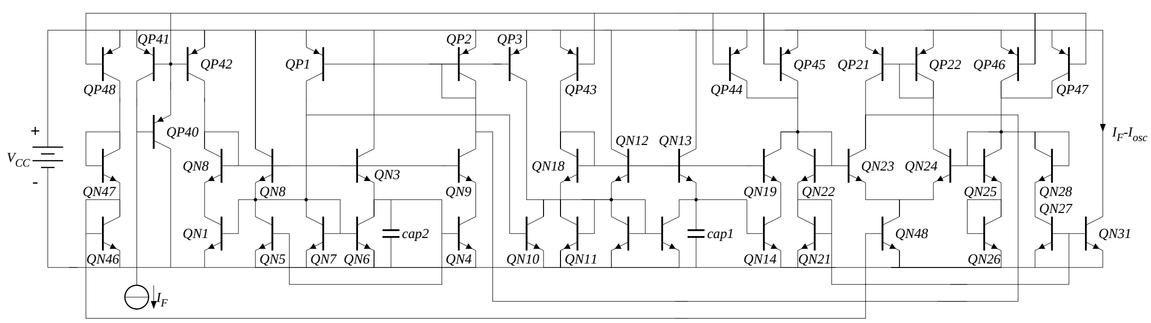

Figure 2: Complete circuit diagram of the translinear oscillator.

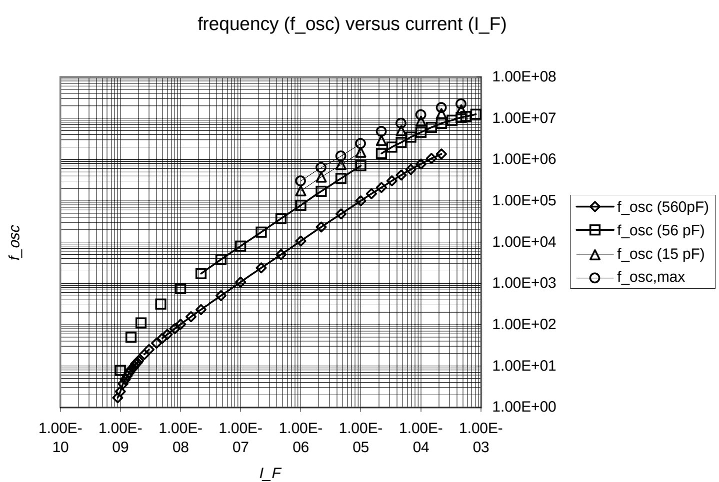


Figure 3: Measured oscillation frequency as a function of control current $I_F$ for four different capacitor values.

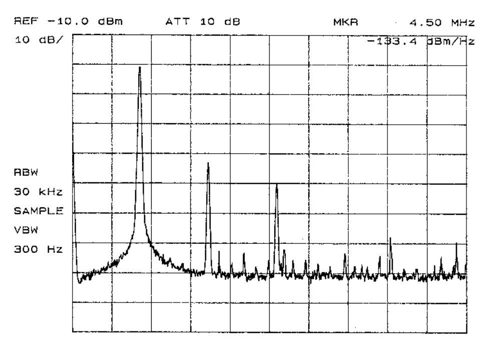


Figure 4: Measured output spectrum for $f_{osc} = 1.7$ MHz.