Square Wave Generator with Voltage-Controlled Frequency Based on Universal Current Conveyor

Abstract. A novel square wave generator (relaxation oscillator) with controllable frequency is described. It employs two universal current conveyors (UCC) and grounded passive elements. The generator includes integrator with two integration capacitors that alternate in charging which results in linear and precise control of frequency by voltage. New implementation of UCC with attractive properties in CMOS 0.18 µm technology is also presented. Computer simulations in PSpice environment confirm the theoretical assumptions.

Streszczenie. W artykule przedstawiono nowy generator fali prostokątnej o regulowanej częstotliwości, zbudowany na bazie dwóch przekaźników prądowych (UCC) oraz elementów pasywnych. Opisano także zastosowanie technologii CMOS 0.18um do przekaźników. Dokonano weryfikacji symulacyjnej w programie PSpice. (Generator fali prostokątnej o napięciowym sterowaniu częstotliwością oparty na uniwersalnych przekaźnikach prądowych).

Keywords: Square Wave Generator, Relaxation Oscillators, Universal Current Conveyor.

Introduction
Square waveform generators with controllable frequency are important circuits used in instrumentation and measurement, for instance for signal processing obtained from sensors [1 - 3]. They have better electromagnetic interference immunity, lower sensitivity and simpler structures compared to harmonic oscillators based on a linear positive feedback structure. Due to these properties, many relaxation oscillators have been published recently [2 - 11]. They employ various active elements and their topology usually consists of a Schmitt trigger (comparator with hysteresis) and an integrator in a closed loop.

Our paper presents a novel square wave generator with two current conveyors, only grounded passive elements and frequency that is linearly controlled by voltage. According to our survey of literature, a circuit with the above mentioned properties has not been published yet. Current conveyors have been chosen due to their wide bandwidth, high slew rate, better accuracy and high dynamic range with low supply voltage. Grounded passive elements are advantageous for integrated implementation.

Universal Current Conveyor
The Universal Current Conveyor (UCC) [12 - 14] has the symbol presented in Fig. 1.

The input-output characteristics of the ideal UCC is described as:

\[
\begin{pmatrix}
V_X \\ I_{Y1+} \\ I_{Y2-} \\ I_{Y3+} \\ I_{Z1+} \\ I_{Z2-}
\end{pmatrix} =
\begin{pmatrix}
1 & -1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
V_{Y1+} \\ V_{Y2-} \\ V_{Y3+} \\ I_X
\end{pmatrix}
\]

(1)

The new CMOS structure of the UCC is presented in Fig. 2 and transistors aspect ratios are given in Table 1. Fig. 3 shows the frequency dependence of the impedances of X, Z+ and Z- terminals with low frequency values 23 mΩ, 0.522 MΩ, and 0.867 MΩ, respectively.
Table 1. Component values and transistor aspect ratios from Fig. 2

<table>
<thead>
<tr>
<th>Component</th>
<th>UCC</th>
<th>W/L [µm/µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1, M2, M01, M02</td>
<td>20/1</td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>10/3</td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>40/3</td>
<td></td>
</tr>
<tr>
<td>M5</td>
<td>50/0.5</td>
<td></td>
</tr>
<tr>
<td>M6, M7</td>
<td>140/0.5</td>
<td></td>
</tr>
<tr>
<td>M8, M9</td>
<td>2/1</td>
<td></td>
</tr>
<tr>
<td>M10, M11, M010, M011</td>
<td>8/1</td>
<td></td>
</tr>
<tr>
<td>M12, M13</td>
<td>120/3</td>
<td></td>
</tr>
<tr>
<td>M14, M15, M21, M22</td>
<td>15/3</td>
<td></td>
</tr>
<tr>
<td>M15c, M23, M24</td>
<td>5/1</td>
<td></td>
</tr>
<tr>
<td>M22c, M25, M26, M27</td>
<td>4/1</td>
<td></td>
</tr>
<tr>
<td>Rb</td>
<td>1 kΩ</td>
<td></td>
</tr>
<tr>
<td>Ib</td>
<td>50 µA</td>
<td></td>
</tr>
<tr>
<td>VDD, -VSS</td>
<td>-2 V</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Frequency dependence of the impedances of X, Z+, and Z- terminals.

Fig. 4 shows the frequency responses of current and voltage gains where the -3dB bandwidths are as follows: $V_{XZ}/V_{Y1}$, $V_{XZ}/V_{Y2}$, $V_{XZ}/V_{Y3}$: 128 MHz, $I_{Z+}/I_{X}$: 22.2 MHz, and $I_{Z-}/I_{X}$: 14.5 MHz.

Fig. 5. Square wave generator based on UCC

The designed square wave generator is shown in Fig. 5. The voltages in the circuit are referenced to ground.

Square wave generator based on UCC

The elements UCC (1), R, C1 and C2 form a voltage integrator. The voltage $V_C$ controls the speed of charging the capacitors and also the frequency of the generated output signal. Providing the voltage $V_C$ is positive, the capacitor $C_1$ charges to positive voltage and $C_2$ to negative. Discharging the capacitors is carried out by the Schmitt trigger (comparator with hysteresis) [11] which consists of UCC (2), R1 and R2. Its input voltage is the sum of $V_{C1}$ and $V_{C2}$. The connection of terminals $Z_+$ and $Z_-$ offers a positive feedback in the circuit. It is necessary to select $R_2 > R_1$ to ensure the positive feedback with a loop-gain higher than unity. The input threshold levels are given as

$$V_{TH} = -V_{TL} = I_{XZ max}(R_2 - R_1)$$

where $I_{XZ max}$ is the lower value of the two currents $I_{X max}$ and $I_{Z max}$ which are the maximum currents that can be supplied by UCC at pins X and Z1 respectively. Relation (2) is exactly valid only for "ideally" limiting conveyor, which means that output current is constant outside a linear operation area. Most real conveyors do not start to limit suddenly at a certain value of input current, but they have rounded transfer characteristics at the transition between linear operation and limiting.

Fig. 6 shows the corresponding waveforms of the generator. It is seen from the waveforms that the circuit operates in two cycles. In one cycle the capacitor $C_1$ integrates the current $I_C$ that is proportional to the input control voltage ($I_C = V_C/R$). In the same cycle the capacitor $C_2$ is charged by the saturation current of the Schmitt trigger flowing through the diode D4. The voltage on $C_2$ quickly reaches the cut-in voltage $V_{D}$ of the diode D2. When the voltage $(V_{C1} + V_{C2})$ reaches $V_{TH}$, the Schmitt trigger changes its state and the second cycle begins. Here the output current of the Schmitt trigger is opposite, $C_1$ quickly discharges through D3 to $-V_D$ and $C_2$ integrates the current until the sum of $V_{C1}$ and $V_{C2}$ reaches $V_{TL}$. Utilization of two capacitors results in better frequency linearity and accuracy. Simple voltage-controlled relaxation oscillators have only one capacitor that integrates the current derived from the control voltage in one cycle and is discharged by Schmitt trigger in the second cycle. The discharging time does not depend on the control voltage and this brings error into the $V - f$ conversion. In our generator, the periods of both cycles are directly proportional to the control voltage. It should be noted that the output of the generator can be chosen also at pin X of UCC. This output is of low impedance. Moreover, a high-impedance current output at terminal $Z_+$ is also available.
The following relation can be derived for the maximum generated frequency

\[ f_{G_{\text{max}}} = \frac{I_{Z_{\text{max}}}}{4CV_{TH}}, \text{ where } C = C_1 = C_2 \]

This ensures that the output current \( I_{Z_{\text{max}}} \) of the Schmitt trigger manages to discharge the capacitor to the cut-in voltage of the parallel diode during the time of one operating cycle at the maximum generator frequency \( f_{G_{\text{max}}} \).

The frequency of the generated signal is

\[ f_G = \frac{V_C}{2RCV_{TH}} \]

Computer simulation

While computing numerical parameters of the circuit and performing its simulations we will consider the parameters of the conveyor described above. The maximum Z-terminal current of the conveyor is \( I_{Z_{\text{max}}} \approx 550 \mu A \). The resistance \( R_2 \) will be chosen 1 kΩ which results in the amplitude of the output voltage \( V_{O1} \) of cca 0.55 V. This is below the maximum pin voltage of the conveyor and thus current (not voltage) limiting occurs at Z1 terminal. If the resistance \( R_1 = 230 \Omega \), the Schmitt trigger threshold voltage is according to (2) \( V_{TH} \approx -V_{TL} \approx 0.42 \text{ V} \). This value is approximately as described below the equation (2). The capacitances \( C_1 = C_2 \) were chosen 0.4 nF which allows maximum frequency \( f_{\text{max}} \approx 812 \text{ kHz} \) according to (3). Finally \( R = 10 \text{ kΩ} \) and diodes were chosen BAT68 Schottky. Fig. 7 shows the waveforms of the capacitor and output voltages with \( V_C = 0.5 \text{ V} \).

Dependency of generator frequency on control voltage is demonstrated in Fig. 8. The slight deviation from linearity is caused by the “non-ideally” limiting conveyor which was already discussed below the equation (2).

Conclusions

Relaxation oscillator employing two universal current conveyors and grounded passive elements has been proposed. Relations and recommendations for computing element parameters have been given. Frequency of generated signal is linearly controlled by voltage with a good accuracy and in a wide range.

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REFERENCES


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