Simple Resistor-less Generator Utilizing Z-copy Controlled Gain Voltage Differencing Current Conveyor for PWM Generation

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Abstract—**This paper deals with a very simple functional generator employing single multi-terminal advanced active device, so-called z-copy controlled gain voltage differencing current conveyor (ZC-CG-VDCC). This active element offers various inter-terminal relations and interesting possibilities of multi-parameter electronic control, which are utilized to control resulting application (triangular and square wave generator). Simple pulse width modulator (PWM) based on two ZC-CG-VDCCs is a further application example of presented generator. Verification of expected behavior was performed by simulation based on CMOS model of the ZC-CG-VDCC and also by lab measurement.**

Index Terms—**Electronic control, functional generator, multiple-terminal advanced active element, PWM, voltage differencing current conveyor, ZC-CG-VDCC.**

I. INTRODUCTION

Advanced or special active elements [1] are useful in circuit synthesis and design from many substantial reasons. First of all, they dispose of various interesting terminal relations [1] useful for simplification of circuit synthesis of standard, advanced or special applications. The next beneficial feature of advanced active elements consists in direct independent electronic control of several parameters included in frame of active device, for example [2]–[5]. Common active elements for circuit design (operational amplifiers for example) realize only one and very simple signal operation ($V_{out} = (V_+ - V_-).A$, where $A \to \infty$) [6], [7] without possibility of electronic control of its parameter(s) in

many cases. Beneficial features of advanced active elements can be also used in the design of functional generators.

Electronically controllable functional (triangular and square wave) generators are widely employed in many analog and digital communication subsystems (clock generation, pulse width modulation, TTL or CMOS logic, DC-DC, AC-DC converters, etc.) [6], [7].

Operational transconductance amplifiers (OTA) [1], [8] were the first active elements that were very suitable for design of generators.

II. DISCUSSION OF RELATED RESEARCH

Siripruchyanun *et al*. [9] and Chung *et al*. [10] proposed a generator based on three adjustable OTAs and three passive elements. Three commercially available active elements were utilized in solution presented in [11], where electronic controllability of the solution was the main contribution.

Another solution employing two (indivisible to sub-blocks) active elements and four passive elements was reported by Janecek *et al*. [12]. However, his work does not focuses on electronic controllability. Chien [13] proposed a generator based on two differential voltage current conveyors (DVCCs) that are multi-terminal active elements, and four passive elements.

Kumbun *et al*. [14] starts with utilization of electronically controllable active elements with active subsections. Their active element, referred to as multiple-output through transconductance amplifiers (MO-CTTA) employs current amplifier with special input feature (sCA) and OTA. Two MO-CTTA are required for construction of the generator. The same number of active devices is required for generators presented by Silapan *et al*. [15]. Silapan *et al*. [15] used two multiple-output current controlled current differencing amplifiers (MO-CCCDTAs) which consist of current differencing unit (CDU) [1], [16], [17] and OTA subsections. A solution presented by Srisakul [18] is based

on multiple-output current controlled current conveyor transconductance amplifier (MO-CCCCTA) where current controlled current conveyor of second generation (CCCII) [1], [19], [20] and OTA create subsections.

Two active elements are sufficient for construction of a functional generator presented in [21], where dual-output voltage differencing buffered amplifier (DO-VDBA) and fully balanced voltage differencing amplifier (FB-VDBA) were employed. These elements are created by internal subsections in a form of operational transconductance amplifier and voltage buffer (VB) or voltage inverter (VI). The proposed generator allows differential outputs of both generated responses.

Single active element, so-called controlled gain current and differential voltage amplifier (CG-CDVA) is sufficient for construction of the generator presented in [22]. Active devices consist of adjustable current amplifier (aCA) and adjustable differential voltage amplifier (DVCA) subsections.

Therefore, a solution of generator, introduced in this paper, offers some significant improvements. Employed active element is not complex and only one element is enough in order to form the generator. Number of external passive elements is decreased to only one grounded capacitor and both signals (square and triangle wave) are available in both voltage and current form. Moreover, functions of our solution are experimentally verified in order to prove the correctness of our concept.

III. ACTIVE ELEMENT DESCRIPTION

Z-copy Controlled Gain Voltage Differencing Current Conveyor (ZC-CG-VDCC) is an active device covering high variability of terminal relations and controllable parameters itself that is highly beneficial for many applications. A detailed principle is discussed in [4] and [5], where we can find also internal CMOS structure that was used for simulations also in this paper. Therefore, we provide only brief explanation of ideal behavior of this multi-terminal active element. Simplified behavioral block model is shown in Fig. 1. In fact, ZC-CG-VDCC is interconnection of two main sub-blocks: OTA and electronically controllable current conveyor of second generation (ECCII) [1]–[3].
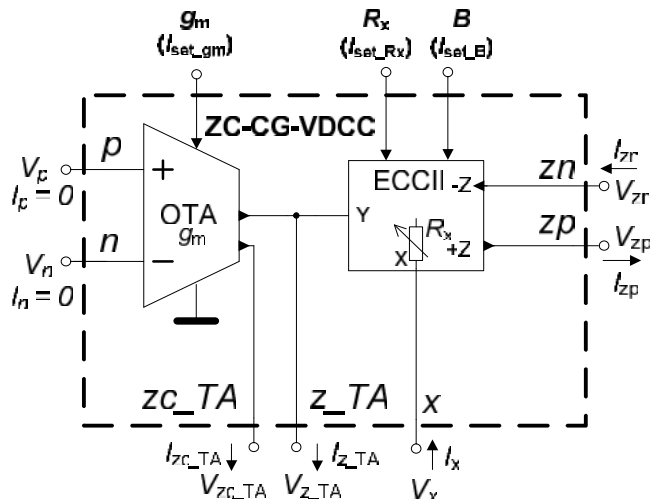

Fig. 1. Behavioral sub-block model of the ZC-CG-VDCC.

Behavior of model in Fig. 1 is defined by:

$$I_{z\_TA} = I_{zc\_TA} = \left(V_p - V_n\right) g_m, \tag{1}$$

$$V_x = V_{z\_TA} + R_x I_x, \tag{2}$$

$$I_{zp} = -I_{zn} = B \times I_x, \tag{3}$$

where controllable parameters are transconductance (g_m)

$$g_m = 2\sqrt{I_{set\_gm} K_{Pn} \frac{W_{M1,2}}{L_{M1,2}}}, \tag{4}$$

internal resistance of current input terminal X (R_X)

$$R_x = \frac{1}{\sqrt{I_{set\_Rx} K_{Pn} \frac{W_{M11,12}}{L_{M11,12}}} + \sqrt{I_{set\_Rx} K_{Pp} \frac{W_{M13,14}}{L_{M13,14}}}}, \tag{5}$$

and current gain B

$$B = \frac{NI_{b2}}{2I_{set\_B}} \cong \frac{I_{b2}}{I_{set\_B}}. \tag{6}$$

Parameters I_{set_gm}, I_{set_RX}, I_{set_B}, I_{b2} are values of internal bias sources of the CMOS structure, W_M and L_M are dimensions of used transistors and K_P are transconductance parameters for used fabrication technology (for more details see [5]).

IV. FUNCTIONAL GENERATOR

The proposed generator in Fig. 2 is formed by two parts: integrator and comparator (Schmitt trigger). We can form these subparts very simply by internal sections of the ZC-CG-VDCC (integrator = capacitor + OTA section, comparator = ECCII section). Square wave is available also in form of current flowing from zc_TA terminal.
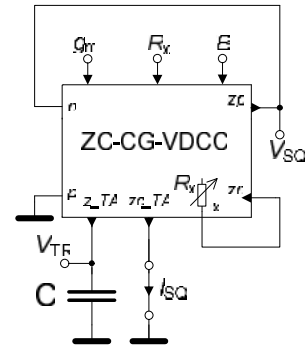

Fig. 2. Triangle and square wave generator based on ZC-CG-VDCC.

A part of the comparator (input z_TA, output zp) has the following principle. The highest current gain in structure of ZC-CG-VDCC has theoretical maximum limited to $B_{max} \approx 4$ [4], [5] for very low DC bias current I_{set_B}. Voltage transfer between z_TA and zn terminals has ideal formula

$$\frac{V_{zn}}{V_{z\_TA}} = \frac{1-B}{1-B}, \tag{7}$$

where transfer has character of unity gain voltage amplifier for $B < 1$. In case of $B \geq 1$, this part of active element behaves as comparator with hysteresis [10]. Direct copy of current I_X (in saturation given by $I_{b1} = 100 \, \mu A$ in [5]) multiplied by gain B is available at terminal zp. Voltage at this terminal is in saturation corner without load resistance. Between zn and z_TA terminals unity gain (7) still persists, therefore threshold input voltages are equal to saturation corners $\pm V_{zn/zn\_sat}$ (approximately ± 0.8 V to ± 0.9 V in our case). Due to this fact, we can obtain equal amplitudes of triangular and square wave response. This statement is valid only for $B \geq 1$ in real case.

Supposing equality of threshold and output level of the repeating frequency is given (for 50 % duty cycle) as

$$f_0 = \frac{I_{set\_gm}}{2 V_{TR\_max} C}, \qquad (8)$$

where $V_{TR\_max} = V_{SQ\_max}$ and 2 in denominator comes from current mirror ratio in CMOS structure [5]. The proposed variant of the generator can also operate with different duty cycle (D) than 50 %, see Fig. 3. Only one additional DC current source is supplemented into the structure.
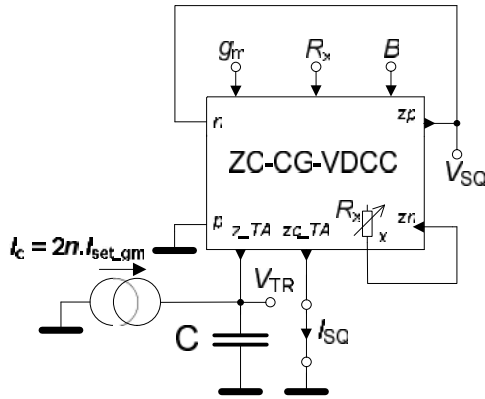

Fig. 3. Triangle and square wave generator with duty cycle control based on ZC-CG-VDCC.

Using routine analysis, we obtain the following expression for repeating frequency

$$f_0 = \frac{I_{z\_TA\_max}\left(1 - \dfrac{I_d}{I_{z\_TA\_max}}\right)\left(1 + \dfrac{I_d}{I_{z\_TA\_max}}\right)}{4 V_{TR\_max} C} =$$

$$= \frac{I_{set\_gm}\left(1 - \dfrac{I_d}{2 I_{set\_gm}}\right)\left(1 + \dfrac{I_d}{2 I_{set\_gm}}\right)}{2 V_{TR\_max} C}, \qquad (9)$$

and duty cycle ($I_{z\_TA\_max} = 2 I_{set\_gm}$)

$$D = \frac{1}{2}\left(1 + \frac{I_d}{2 I_{set\_gm}}\right) = \frac{1}{2}(1 + n), \qquad (10)$$

where $n = I_d / 2 I_{set\_gm}$ and represents relation between D and f_0. (I_d is theoretically limited to $\pm 2 I_{set\_gm}$). Constant 2 is also given by multiplication of current mirrors in OTA section in

frame of the ZC-CG-VDCC element (see [5]). Setting of D independently of f_0 is also possible for constant ratio $n = 2D - 1$ ($I_d = 2 \cdot I_{set\_gm}(2D - 1)$). Accurate ratio of two DC currents is quite easily available in IC design.

V. SIMULATION RESULTS

A. Functional Generator

We obtained the following simulation results for parameters: $C = 40$ pF, $R_x = 1$ kΩ ($I_{set\_Rx} = 34 \, \mu A$), $g_m = 1$ mS ($I_{set\_gm} = 54 \, \mu A$), $B = 2$ ($I_{set\_B} = 58 \, \mu A$). Transient responses (V_{TR}, V_{SQ}) are given in Fig. 4 for theoretical $f_0 = 0.844$ MHz. The repeating frequency obtained from simulation was 0.904 MHz. The triangle wave signal has inverting polarity (consequence of inverting Schmitt trigger). Tuning of the generator (Fig. 5) was verified from 109 kHz to 1479 kHz by adjusting of I_{set_gm} from 5 µA to 99 µA (ideal range of f_0 control is 78 kHz−1 547 kHz). Range of the adjusting is proportional to I_{set_gm}.
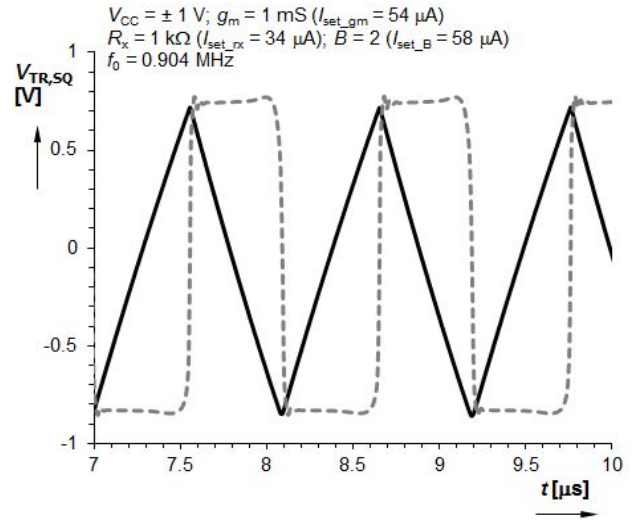

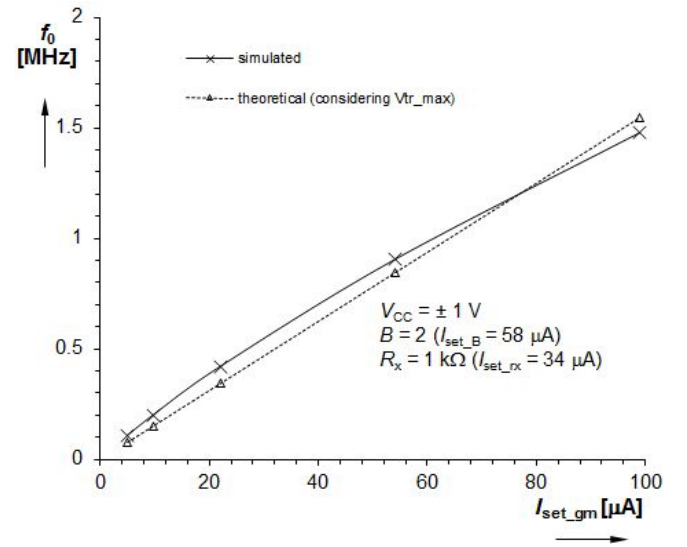Fig. 4. Transient responses of the generator from Fig. 2 (V_{TR}, V_{SQ}).

Fig. 5. Dependence of the repeating frequency on DC bias current I_{set_gm}.

The results of exemplary f_0 tuning for two different frequencies and $D = 30$ % or 70 % (simulated as 29.7 % and 30.8 % or 66.9 % and 69.7 %) are given in Fig. 6 and Fig. 7. Utilization of current output terminal zc_TA (resistive load at

this terminal) allows to obtain differential voltage output of the square wave that is useful in low-voltage and low power applications, where voltage swing is very limited.
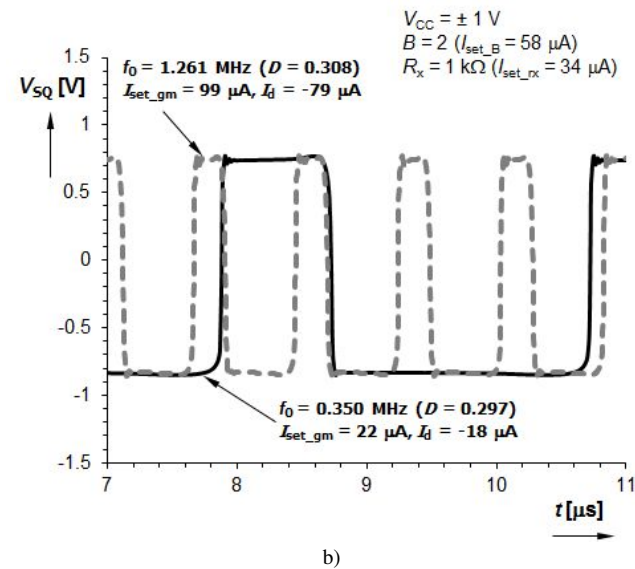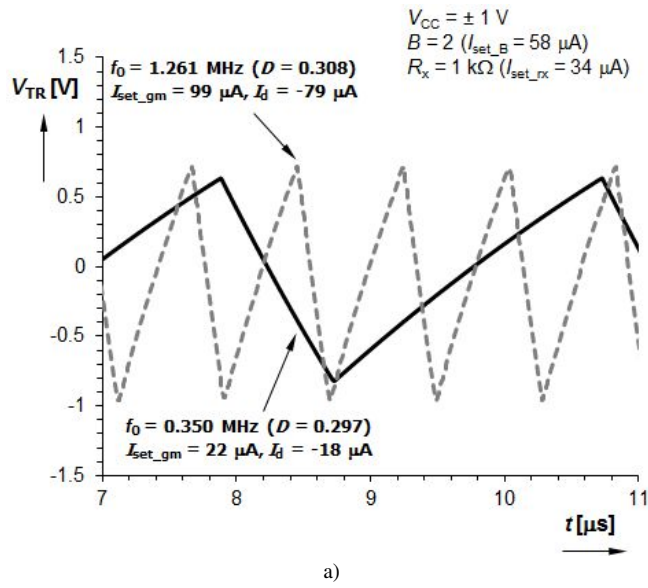

a)

b)

Fig. 6. Transient response for f_0 adjusting with $D = 30$ %: a) triangle wave, b) square wave.
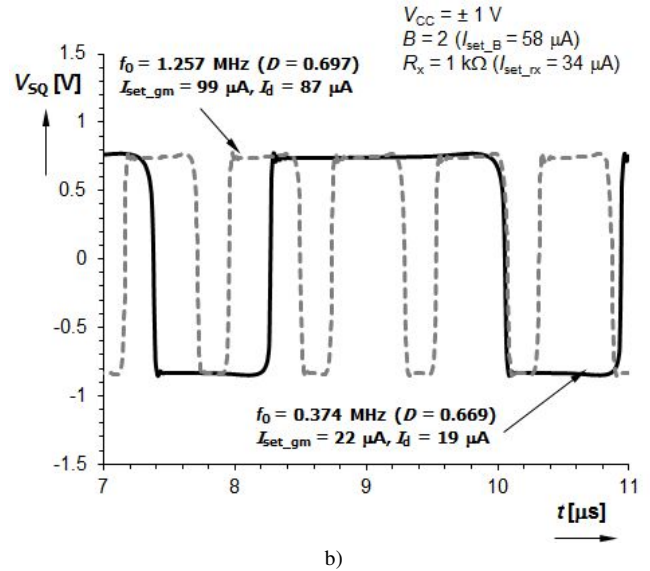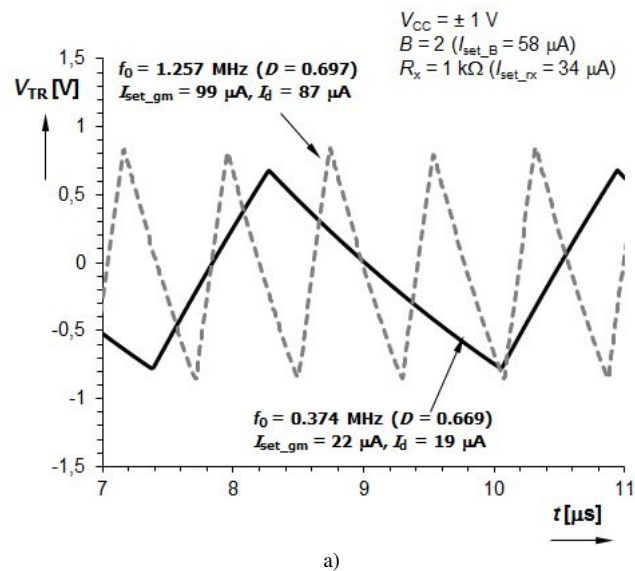

a)

b)

Fig. 7. Transient response for f_0 adjusting with $D = 70$ %: a) triangle wave, b) square wave.

B. PWM Modulator

Pulse width modulator (PWM) [23] is both quite important and typical application of the functional generator. PWM modulators are frequently used in power supply sources/converters (DC-DC, AC-DC) and high-efficient audio amplifiers (D class) for example. We established the following PWM modulator (Fig. 8) as a simple example of utilization of the triangular wave output of the generator. Two ZC-CG-VDCCs are sufficient to provide simple PWM modulator employing low number of passive elements (one R and one C only). Input OTA section of the ZC-CG-VDCC$_2$ which is directly connected to the current conveyor CCII input Y (z_TA) forms simple comparator without hysteresis. Output response is available after internal voltage buffer in frame of CCII part (at X terminal).
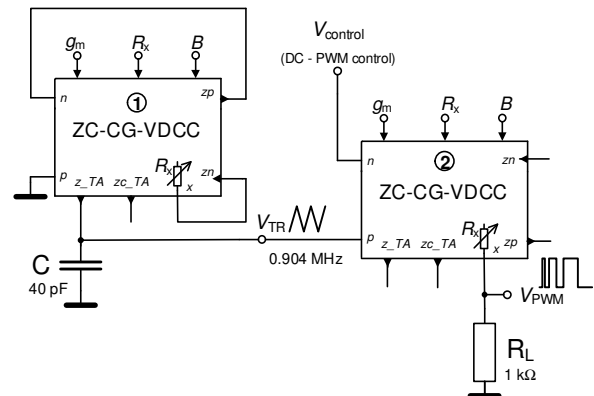

Fig. 8. A simple pulse width modulator based on two ZC-CG-VDCC.

Output of the PWM is terminated by load resistance 1 kΩ and rest of terminals (ZC-CG-VDCCs) was kept unconnected or grounded. Configuration of the modulator was set as: repeating frequency 0.904 MHz, $C = 40$ pF. Additional parameters (bias currents) are noted in figures including simulation results (Fig. 9). We tested system in two situations: a) linear sweep of DC control voltage ($V_{control}$) from −0.8 V to 0.8 V and b) harmonic excitation (1.1 V_{p-p}, 50 kHz).
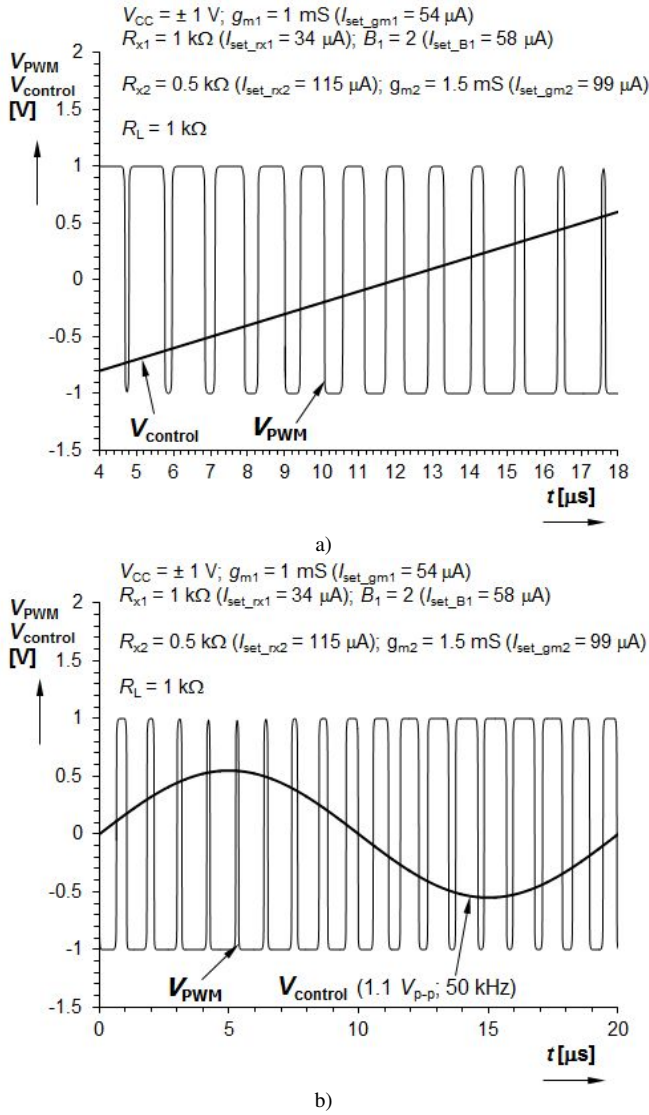
a)

b)

Fig. 9. Results of the PWM modulator simulation: a) example of linear sweep, b) example of harmonic excitation.

$$f_{0\_m} \cong \frac{V_{SET\_gm}}{4R_k'C}. \qquad (11)$$

The equation (11) is different than previous derivations because model in Fig. 10 only emulates behavior of the ZC-CG-VDCC device and it has not exactly the same principle of operation as CMOS model of ZC-CG-VDCC in [5].
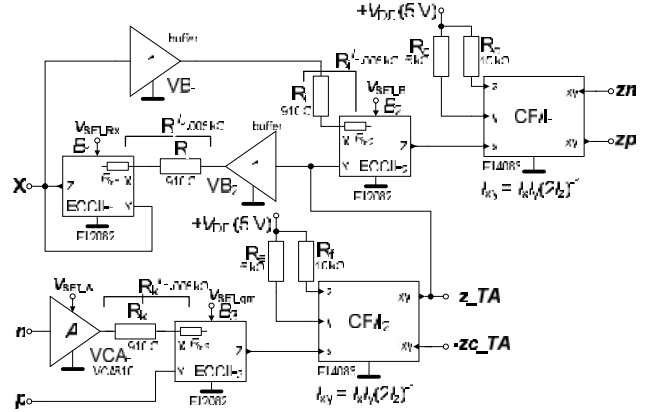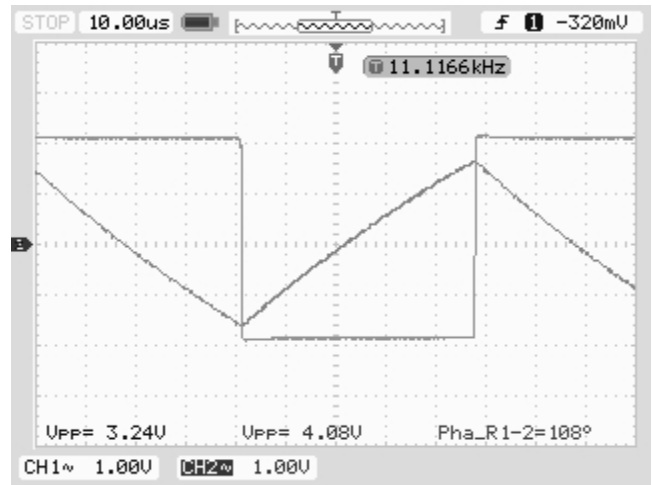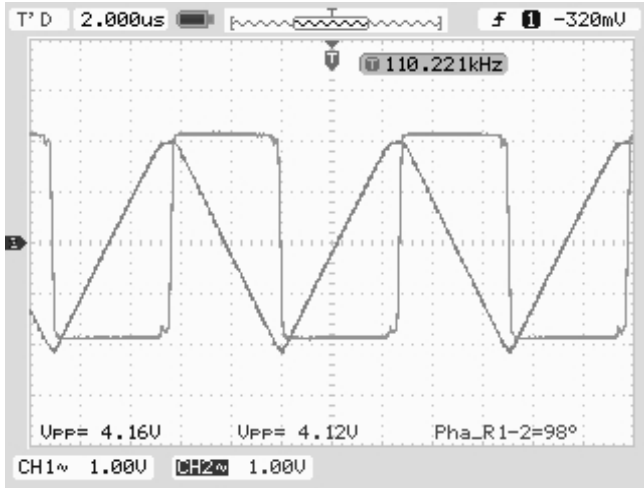

Fig. 10. Behavioral model of ZC-CF-VDCC (concept from Fig. 1) consisting of commercially available active devices.

As an example, transient responses of triangle and square wave signals with $D = 50$ %, and $f_0 = 11.1$ kHz ($V_{SET\_gm} = 0.04$ V), $f_0 = 110$ kHz ($V_{SET\_gm} = 0.63$ V) were selected (Fig. 11) were obtained for $C = 1$ nF. Values of other parameters and constants during tests are noted in the following Fig. 12. Dependence of f_0 on V_{SET_gm} and dependence of output levels (peak-to-peak) on f_0 are shown in Fig. 12. Validity of approximate equation (11) was verified by measurement (Fig. 12) up to 80 kHz ($V_{SET\_gm} = 0.32$ V). As obvious from the graph, further increasing of V_{SET_gm} causes problems with linearity of transfer characteristics and problems with slew-rate. Proposed behavioral model is obviously not suitable for high frequency operation with large signal levels (it reaches supply saturation corners in our case – see square waves in the graph), due to existence of high impedance node with large parasitic capacitance (frequency dependent impedance) of node of V_{SQ}, where terminals n and zp are interconnected.

VI. MEASUREMENT RESULTS

Triangle and square wave generator based on ZC-CG-VDCC (Fig. 2) was implemented to be measured in lab. Behavioral model of ZC-CG-VDCC consisting of commercially available active devices was prepared for such a reason. Prepared behavioral model is depicted in Fig. 10. The subpart consisting of ECCII$_1$, ECCII$_2$, VB$_1$, VB$_2$ and CF/I$_1$ (CF/I – current follower and inverter) emulates overall ECCII section in Fig. 1. The rest of blocks (VCA$_1$, ECCII$_3$, CF/I$_2$) represents OTA section in Fig. 1. Three adjustable parameters [11], [24] of the basic model in Fig. 1 are defined as: $R_X \cong R_j'/V_{SET\_Rx}$, $B \cong V_{SET\_B}$ and $g_m \cong V_{SET\_gm}/R_k'$. Our model includes also additional parameter A (voltage gain) that is suitable for further development of applications (additional degree of freedom) that is available in relation between I_{z_TA} (I_{zc_TA} and V_p and V_n) as: $(V_p - V_n A)g_m = I_{z\_TA} = -I_{zc\_TA}$, where $A \cong 10^{-2(V_{SET\_A}+1)}$.

We used discussed behavioral model for verification of proposed generator in Fig. 2. Supposing equality of amplitudes of generated waveforms ($V_{SQ\_max} = V_{TR\_max}$), approximate equation for f_0 has it this case form
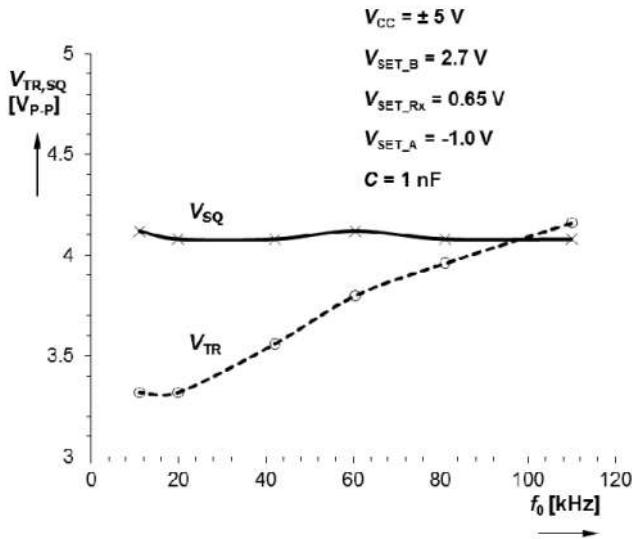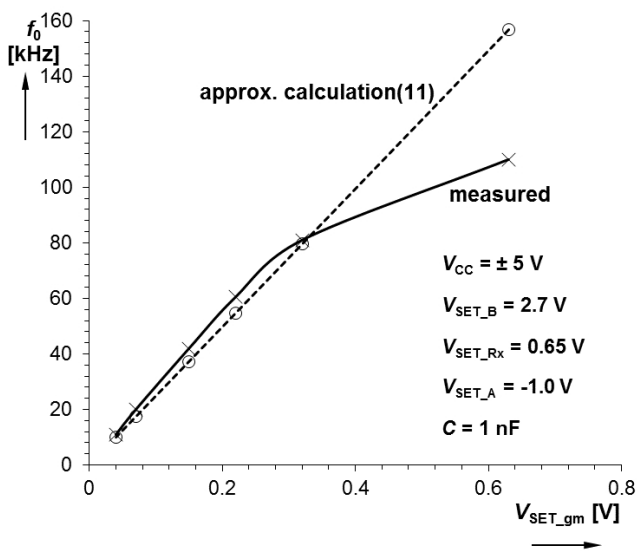

a)

b)

Fig. 11. Measured transient responses for f_0 adjusting with $D = 50 \%$ of the generator from Fig. 2 based on behavioral model in Fig. 10: a) $f_0 = 11$ kHz, b) $f_0 = 110$ kHz.

a)

b)

Fig. 12. Measured dependences of: a) output levels on f_0, b) f_0 on V_{SET_gm}.

VII. CONCLUSIONS

Presented functional generator requires only one active

element and really low number of external passive elements (one capacitor only) and moreover it provides outputs (square and triangle wave) in both voltage and current form. By utilizing CMOS model of the active device from [5] we obtained very large adjustability range from 109 kHz to 1479 kHz by adjusting of I_{set_gm} from 5 µA to 99 µA. For comparison with already published solutions see Table I, where a brief overview was provided. Note that our work includes also real measurement results that prove the design correctness. Behavioral model suffers from the significant parasitics that limit useful bandwidth in this case, as was discussed in previous section, therefore it was measured in 11 kHz to 110 kHz range. Proposed generator can be used for PWM modulation by a very simple way – a part of additional active device is used for comparisons of triangular wave with constant DC component to create PWM signal. All adjustable parameters (g_m, R_X, B) of the ZC-CG-VDCC were not necessary in the presented applications. Engagement of all controllable features is fully utilized in reconnection-less reconfigurable active filters [5] or multiphase oscillators [4] for example. Note that the generator can be obtained also if internal subsections (Fig. 1) of the ZC-CG-VDCC are interchanged (integrator is created by ECCII and comparator by OTA section) [25]. However, solution presented here saves two resistors.

TABLE I. COMPARISON OF SELECTED GENERATOR SOLUTIONS.

Reference	No. of active/passive elements	Abbreviation of active element or elements	Internal subsections	Available current and voltage output of square wave type	Differential square wave outputs available	Type of output signals (current or voltage)
[9], [10]	3/3	OTA	-	No	No	Voltage
[11]	3/2	2x VCA + DT + VB	-	No	No	Voltage
[12]	2/4	CCII + UCC + 4 diodes	-	N/A	Yes	Voltage
[13]	2/4	DVCC	-	No	N/A	Voltage
[14]	2/1	MO-CTTA	sCA+OTA	N/A	N/A	Current
[15]	2/1	MO-CCCDTA	CDU+OTA	N/A	N/A	Current
[18]	2/1	MO-CCCCTA	CCCII+OTA	N/A	N/A	Current
[21]	2/3	DO-VDBA, FB-VDBA	OTA+VB+VI	Yes	Yes	Both
[22]	1/2	CG-CDVA	aCA+DVCA	No	No	Voltage
[25]	1/3	ZC-CG-VDCC	OTA+ECCII	Yes	Yes	Both
Fig. 2	1/1	ZC-CG-VDCC	OTA+ECCII	Yes	Yes	Both

Note: N/A – information is not available or verified

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