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Second-Order Simple Multiphase Oscillator Using Z-Copy Controlled-Gain Voltage Differencing Current Conveyor

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***Abstract*—Interesting type of the second-order electronically controllable multiphase oscillator is introduced in this paper. Modified voltage differencing current conveyor, so-called z-copy controlled gain voltage differencing current conveyor (ZC-CG-VDCC), offers interesting features for synthesis of this type of multiphase oscillator. Available controllable parameters of the ZC-CG-VDCC (intrinsic resistance, transconductance and current gain) are fully utilized for independent adjusting of oscillation condition and oscillation frequency. Specific matching condition allows linear control of oscillation frequency that is not so typical in such simple types of oscillators. Available phase shifts are 45, 90, 135 and 180 degree. Simulation results based on CMOS model of active element confirms intentions of the proposal in the bandwidth of several MHz.**

***Index Terms*—Electronic control, current-gain, intrinsic resistance, second-order multiphase oscillators, transconductance, voltage differencing current conveyor, z-copy.**

I. INTRODUCTION

Applications of more than one type of controllable parameter in frame of one active device have increasing attention of many researchers. Several interesting solutions of active element with these features were reported in literature. For example, Minaei et al. [1], Marcellis *et al.* [2], Kumngern et al. [3] and others presented interesting conceptions. Extended version of the current conveyor introduced in [1] allows adjustable current gain (B) between x and z terminals and adjustable intrinsic resistance (R_x) of the current input terminal x. Modified current conveyor introduced in [2] disposes controllable features of current gain between x and z terminals and voltage gain between y and x terminals. Combination of R_x and B control is available in interesting version of translinear current conveyor [3]. Typical examples of active elements with two-parameter control are also modifications of the current differencing transconductance amplifier (CDTA) [4], [5]. DC bias currents are also used for control of R_x and transconductance g_m [6], [7]. Transconductance section [4], [8] combined with current conveyor of second generation [4], [9], [10] are common subparts in so-called current conveyor transconductance amplifier (CCTA) [4], [11], where independent R_x and g_m control is also possible [12]. Some modifications of CCTA provide also adjustable current gain control [13].

Active element presented in this paper and used in proposed application offers possibility of control of three independent parameters. In case of oscillator, it is fully utilized for control of oscillation condition and linear tuning of oscillation frequency.

The reasons for utilization of active elements employing several types of electronic control came from requirements for comfortable electronic control in applications. The important applications in the field of signal generation are oscillators. Therefore, we provided detailed study of several oscillator solutions and found following drawbacks concerning mainly lack of electronically controllable features of proposed circuits:

1. too many passive elements (for example [14]–[17]),
2. condition of oscillation given by equality of capacitors only (for example [18]–[22]),

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TABLE 1. SOME OF RECENTLY REPORTED SOLUTIONS OF SIMPLE SECOND-ORDER MULTIPHASE OSCILLATORS.

Reference	Year	No. of active elements	No. of passive elements	Type of active element	Tunable type	Grounded C	Mutual dependence of oscillation frequency and condition	Electronic control of oscillation frequency	Electronic control of oscillation condition	Type of control (PE- passive elements-resistor; DC V - DC bias voltage; DC I - DC bias current)	Type of the phase shift (multiplicand)	Type of output signals (current or voltage)
[6]	2012	2	2	CCCDTA	Yes	Yes	No	Yes (g_m)	Yes (g_m)	DC I	$k\pi/2$	current
[31]	2011	2	5 or 6	DO-CIBA	Yes	Yes	No	No (R)	No (R)	PE	$k\pi/2$	voltage
[32]	2013	2	3	VDIBA	No	No	Yes	Yes (g_m)	Yes (g_m)	DC I	$k\pi/2$	voltage
[33]	in press	3	5	DO-CG-CFBA	Yes	Yes	No	Yes (B)	Yes (B)	DC V	$k\pi/2$	voltage
[34]	2014	2	5	CG-CFDOBA, CG-BCVA	Yes	Yes	No	Yes (B)	Yes (A)	DC V	$k\pi/2$	voltage
[35]	2012	1	3	VDTA	Yes	Yes	No	Yes (g_m)	No (R)	DC I	$k\pi/2$	current
[36]	2013	1	5	VDTA	Yes	Yes	No	Yes (g_m)	No (R)	DC I	$k\pi/2$	voltage
[37]	2012	2	6	CCII+. ECCII-	No	Yes	No	No	Yes (B)	DC V	$k\pi/4$	voltage
[38]*	2013	2	3; 5	DO-VDBA, FB-VDBA	No	Yes	No; Yes	Yes(g_m); No	Yes (g_m)	DC I	$k\pi/4$	voltage
proposed		1	4	ZC-CG-VDCC	Yes	Yes	No	Yes (g_m, R_x)	Yes (B)	DC I	$k\pi/4$	voltage

Notes: A – voltage gain; B – current gain; g_m – transconductance; R – resistor value
** ref. [38] deals with two types of the oscillator with phase shift $k\pi/4$*

3. matching of two controllable parameters or values of passive elements required in order to fulfill oscillation condition, and tuning of oscillation frequency is required simultaneously [18]–[22],
4. linear control of oscillation frequency is not possible especially in simple solutions having minimal number of active elements [23]–[28],
5. none of discussed simple second-order solution allow four-phase outputs with $\pi/4$ shift i.e. 45, 90, 135, and 180 degree of phase shifts.

Of course, there are many multiphase solutions based on cascades (chains) of lossy blocks in one loop (for example [29] and references cited therein) that allow various phase shifts, but circuit realization is very extensive (many active and passive elements) and tunability complicated in some cases [30]. Therefore, we focused our attention on simple (minimal number of active element) electronically adjustable solutions. Despite of fact that several second-order multiphase and tunable oscillators were introduced [6], [31]–[36], any solution from them does not allow to realize phase shift between produced signals different than $\pi/2$. Detailed comparison is shown in Table I. Our solution produces phase shift $\pi/4$ between generated signals. The same feature is available in [37], [38], but discussed solutions do not have capability of electronic control (or any other method) of oscillation frequency or they do not have independent control of oscillation frequency (element suitable for frequency control influences oscillation condition). Therefore, oscillator presented in this paper provides significant advantages (electronic control of oscillation frequency independently on oscillation condition and minimal number of active elements) in comparison to previous works that realizes phase shift in multiples of $\pi/4$ [37], [38].

II. SECOND-ORDER MULTIPHASE OSCILLATOR USING Z-COPY CONTROLLED-GAIN VOLTAGE DIFFERENCING CURRENT CONVEYOR

Presented second-order multiphase oscillator utilizes active element referred as z-copy controlled gain voltage differencing current conveyor (ZC-CG-VDCC). Detailed description of the active element and its parameters are discussed in [39]. Therefore, only very brief introduction is given here. ZC-CG-VDCC is multi-terminal mixed-mode active device that provides three independent types of controllable parameters (R_x, g_m, B). These parameters are adjustable by DC bias currents. Difference of voltages V_p and V_n at high-impedance input terminals is transformed to current I_{z_TA} by transconductance section (g_m). The identical copy is provided for auxiliary purposes (high-impedance terminal zc_TA). Voltage at low-impedance current input terminal x is directly given by intrinsic resistance R_X and V_{z_TA}. Current $I_x = (V_x - V_{z\_TA})/R_x$ is amplified by adjustable gain B to positive and negative output (high-impedance terminals z_p, z_n). Symbol, including internal behavioral model, is shown in Fig. 1. Outgoing current (arrow in direction out of the device) is meant as positive. Inter-terminal relations are also included in Fig. 1. Possible CMOS implementation and its features are shown in [39].

Circuit structure of the multiphase voltage-mode oscillator is given in Fig. 2. Here it is worth to note that the circuit can also work in current-mode if the load resistances R_{L1} and R_{L2} are omitted. In this case current responses are taken from terminals zp and zc_TA. Characteristic equation of the oscillator in Fig. 2 has very favorable form

$$s^2 + \frac{C_2 - C_1 B}{R_x C_1 C_2} s + \frac{g_m}{R_x C_1 C_2} = 0, \tag{1}$$

where condition of oscillation (CO) and frequency of oscillation (FO) are:

$$B \geq \frac{C_2}{C_1}, \tag{2}$$

$$\omega_0 = \sqrt{\frac{g_m}{R_x C_1 C_2}}. \tag{3}$$

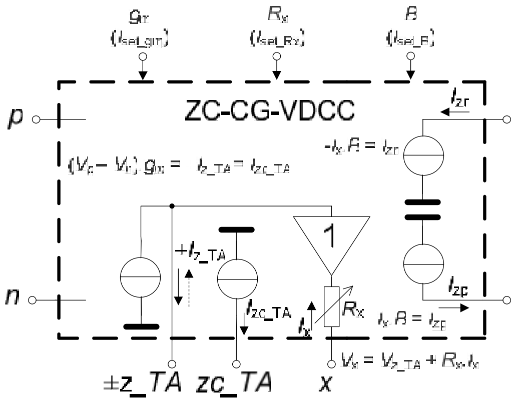


Fig. 1. Symbol and behavioral model of the ZC-CG-VDCC.

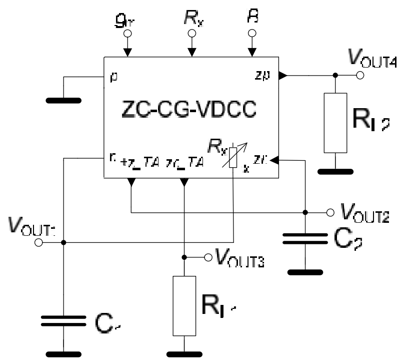


Fig. 2. ZC-CG-VDCC based second-order simple multiphase oscillator.

The relation between outputs V_{OUT2} and V_{OUT1} is represented by following expression

$$\frac{V_{OUT2}}{V_{OUT1}} = \frac{B + R_x g_m}{B - sC_2 R_x}. \tag{4}$$

If CO ($B = 1$) is fulfilled and $g_m = 1/R_x$, $C_1 = C_2 = C$, (4) can be simplified to

$$\frac{V_{OUT2}}{V_{OUT1}} = 1 + j, \tag{5}$$

that gives

$$V_{OUT2} = \sqrt{2}\exp(j\pi/4)V_{OUT1}. \tag{6}$$

Relation for V_{OUT4} and V_{OUT1} has a form

$$\frac{V_{OUT4}}{V_{OUT1}} = R_{L2} B \frac{sC_2 + g_m}{sC_2 R_x - B}. \tag{7}$$

Simplified relation ($g_m = 1/R_x$, $C_1 = C_2 = C$, $B = 1$), valid at FO, has a form:

$$\frac{V_{OUT4}}{V_{OUT1}} = -R_{L2} g_m j = -\frac{R_{L2}}{R_x} j, \tag{8}$$

$$V_{OUT4} = R_{L2} g_m \exp(-j\pi/2) V_{OUT1}. \tag{9}$$

Between V_{OUT3} and V_{OUT1} we achieve very simple relation (for discussed simplification):

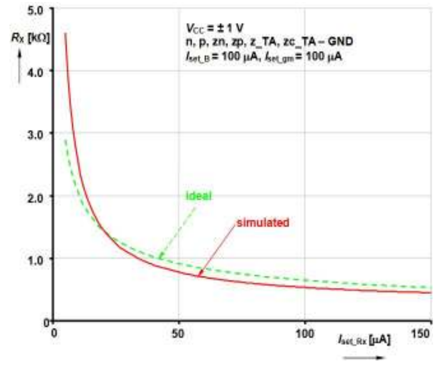
$$\frac{V_{OUT3}}{V_{OUT1}} = -\frac{R_{L1}}{R_x} = -R_{L1} g_m, \tag{10}$$

$$V_{OUT3} = R_{L1} g_m \exp(j\pi) V_{OUT1}. \tag{11}$$

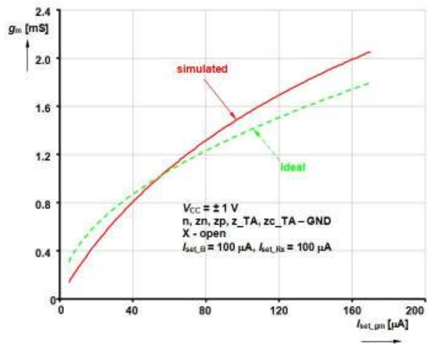
Detailed evaluation of above noted relations shows that phase shifts keep preserved during the tuning process if considered conditions ($g_m = 1/R_x$, $C_1 = C_2 = C$) are ensured. However, as we can see, amplitudes of two of produced signals (V_{OUT3}, V_{OUT4}) vary during the tuning process. Oscillation frequency can be adjusted linearly by g_m and R_x simultaneously while their ratio is kept constant.

III. SIMULATION RESULTS

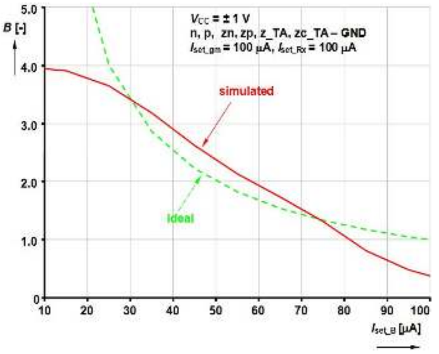
We used CMOS model of the ZC-CG-VDCC introduced in [39] for verification and analysis of proposed circuit. Controllability of discussed parameters (R_x, g_m, B) of the ZC-CG-VDCC CMOS model from [39] is documented in Fig. 3. Ideal traces are determined from theoretical equations for R_x, g_m, and B in accordance with the CMOS model specifications [39]. Adjusting of the DC bias current I_{set_Rx} between 5.9 μA and 80 μA allows control of R_x in approximate range from 4 kΩ to 0.67 kΩ. Transconductance control is in case of this proposed oscillator sufficient from 250 μS to 1500 μS by I_{set_gm} between 9.7 μA and 99 μA. Current gain control B is in range 0.4 to 4 (I_{set_B} from 100 μA to 10 μA).



a)



b)



c)

Fig. 3. Typical dependences of controllable parameters of ZC-CG-VDCC element [39] on DC bias control currents: a) R_x, b) g_m, c) B.

The oscillator in Fig. 4 (including circuit for amplitude stabilization) was designed with following parameters: $C_1 = C_2 = 30$ pF, $R_x = 2$ kΩ ($I_{set\_Rx} = 13.3$ μA), $g_m = 500$ μS ($I_{set\_gm} = 22$ μA), $B \approx 1$ (control current had to be varied in range $I_{set\_B} \approx 79$ μA–81 μA). Supply voltage was ± 1 V. Values of load resistance are $R_{L1} = R_{L2} = 2$ kΩ. Ideal oscillation frequency has value 2.654 MHz.

Ideal phase and amplitude relations based on analysis in (4)–(11) for these initial parameters and discrete frequency are given in Fig. 5. Dots at the ends of lines of the constant vectors mean constant unchangeable positions (obvious at single FO value). Nonlinear tuning process based on fixed R_x and adjusted g_m is possible. However, amplitude (V_{OUT3} and V_{OUT4}) and also additional amplitude and phase changes between V_{OUT1} and V_{OUT2} occur, see Fig. 6 for further information, where dynamical output vectors in polar plot are shown (arrows signalize trends of amplitude changes with increasing g_m from 100 μS to 1 mS). Voltage V_{OUT1} has always constant value. Simultaneous control of both parameters ($g_m = 1/R_x$) is the best choice for the operation of proposed system. Figure 7 shows that V_{OUT2} keeps constant for $g_m = 1/R_x$ control of FO. Amplitudes of V_{OUT1} and V_{OUT2} are not equal but their ratio keeps invariant in process of tuning and levels are constant (dot at the end of line of the vectors). Unfortunately, V_{OUT3} and V_{OUT4} are still dependent on FO control.

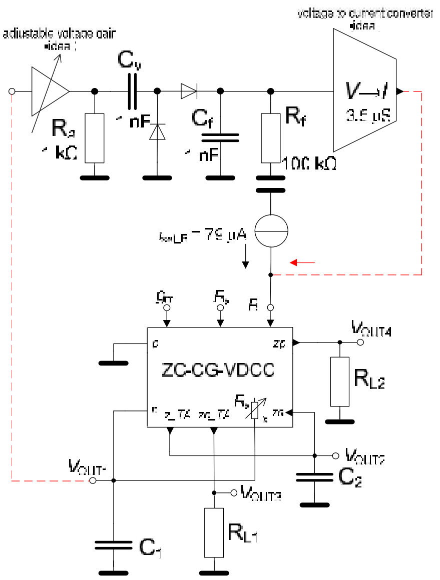


Fig. 4. Simulated oscillator circuit including automatic gain control circuit for amplitude stabilization.

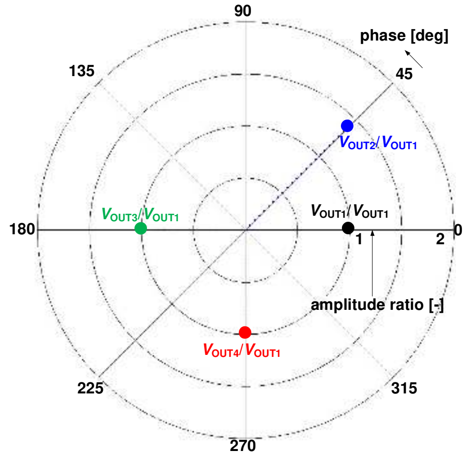


Fig. 5. Phase and amplitude relations between available outputs of ideal oscillator (f_0 = 2.65 MHz) in polar plot.

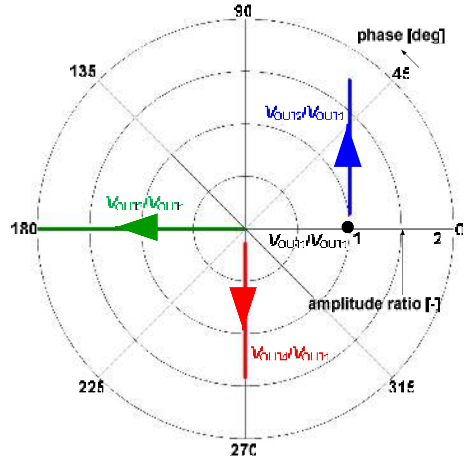


Fig. 6. Polar plot of output vector voltage relations for g_m and FO adjusting from 100 μS to 1 mS (fixed R_x = 2 kΩ).

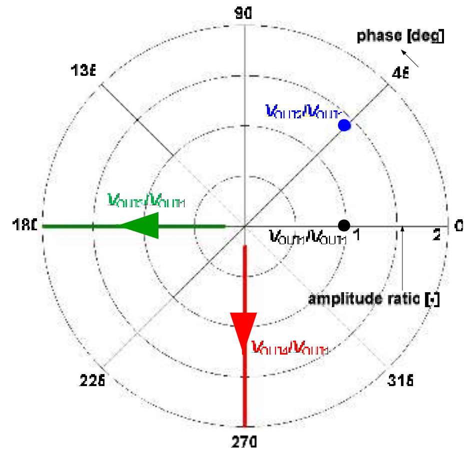


Fig. 7. Polar plot of output vector voltage relations for control of FO by $g_m = 1/R_x$ simultaneous adjusting from 100 μS to 1 mS.

Value of FO, obtained from simulation, achieved 2.566 MHz. Simulation results are shown in Fig. 8, where transient responses for all four outputs are available. Simulated phase shifts were 44 degrees (V_{OUT1}-V_{OUT2}), 86 degrees (V_{OUT1}-V_{OUT4}), 181 degrees (V_{OUT1}-V_{OUT3}) and 139 degrees (V_{OUT2}-V_{OUT4}).

The FO control supposes simultaneous change of g_m and R_x. Theoretical range of FO control allows control in between 1.327 MHz–7.960 MHz ($g_m = 1/R_x$ = <0.25; 1.5> mS). Simulations provided adjusting from 1.331 MHz to 7.391 MHz. Corresponding results are in Fig. 9. Amplitudes of V_{OUT3} and V_{OUT4} still changes in accordance to discussed theoretical relations (V_{OUT1} and V_{OUT2} are unchangeable if equality $g_m = 1/R_x$ is ensured).

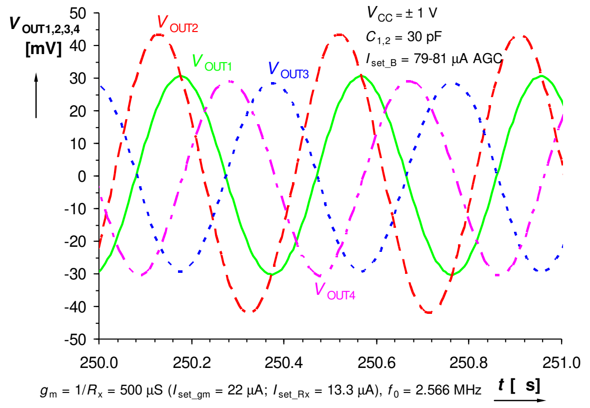


Fig. 8. Transient responses of all available outputs.

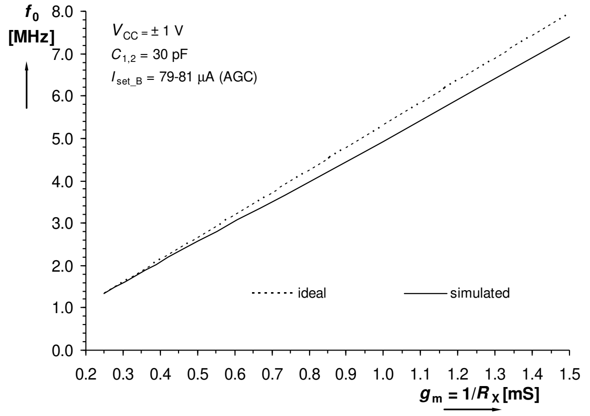


Fig. 9. Dependence of oscillation frequency on $g_m = 1/R_x$.

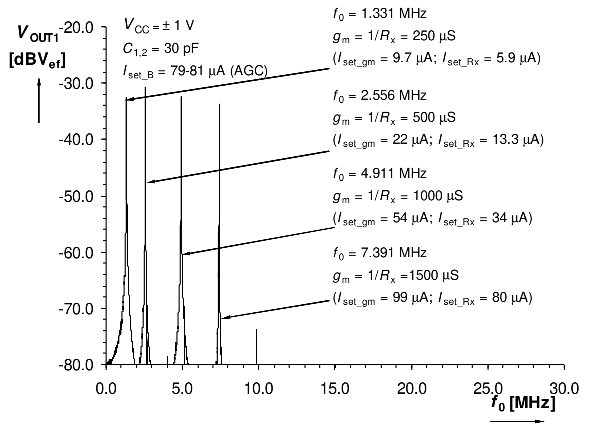


Fig. 10. Frequency spectrum of V_{OUT1} for selected oscillation frequencies.

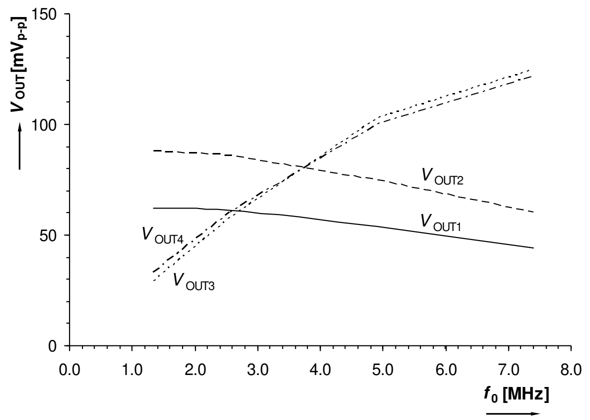


Fig. 11. Dependences of output levels on oscillation frequency.

Frequency spectrum of V_{OUT1} for four discrete frequencies is shown in Fig. 10. Figure 11 shows dependence of output levels on tuning process. It confirms theoretical relations (4)–(15). Total harmonic distortion (THD) results obtained at all available outputs are shown in Fig. 12 and reach 0.45 %–3.8 % (V_{OUT1}: 0.45 %–1.48 %; V_{OUT2}: 0.45 %–2.28 %; V_{OUT3}: 0.58 %–3.81 %; V_{OUT4}: 1.17 %–3.15 %) in whole range of oscillation frequency tuning. Last plot shows power consumption of the oscillator that has very slight dependence on tuning process (Fig. 13).

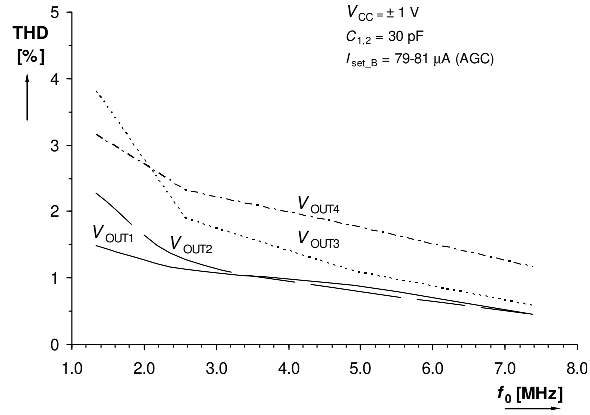


Fig. 12. Dependences of THD on oscillation frequency.

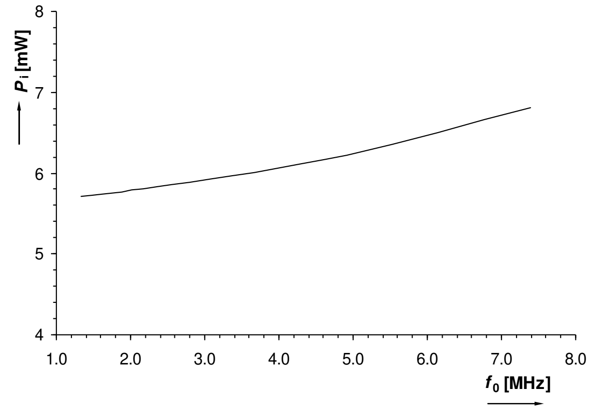


Fig. 13. Dependence of power consumption on oscillation frequency.

IV. CONCLUSIONS

The proposed simple second-order sinusoidal oscillator fulfils multiphase requirements (produces 45, 90, 135 and 180 degree phase shifts simultaneously) and can work also as the quadrature type. The matching of two parameters is required for linear electronic control of the oscillation frequency. Nevertheless, this matching is easily accessible by adjusting of both parameters (transconductance g_m and intrinsic resistance of the current input R_x). The third parameter (current gain B) controls the condition of oscillation. All parameters are controlled electronically. Verification of tuning was provided from 1.331 to 7.391 MHz.

REFERENCES

[1] S. Minaei, O. K. Sayin, H. Kuntman, “A new CMOS electronically tunable current conveyor and its application to current-mode filters”, *IEEE Trans. on Circuits and Systems - I*, vol. 53, no. 7, pp. 1448–1457, 2006.

[2] A. Marcellis, G. Ferri, N. C. Guerrini, G. Scotti, V. Stornelli, A. Trifiletti, “The VGC-CCII: a novel building block and its application to capacitance multiplication”, *Analog Integrated Circuits and Signal Processing*, vol. 58, no. 1, pp. 55–59, 2009. [Online].

Available: http://dx.doi.org/10.1007/s10470-008-9213-6

[3] M. Kumngern, S. Junnapiya, "A sinusoidal oscillator using translinear current conveyors", *in Proc. Asia Pacific Conf. on Circuits and Systems APPCAS2010*, Kuala Lumpur, 2010, pp. 740–743.

[4] D. Biolek, R. Senani, V. Biolkova, Z. Kolka, "Active elements for analog signal processing: classification, review and new proposals", *Radioengineering*, vol. 17, no. 4, pp. 15–32, 2008.

[5] A. U. Keskin, D. Biolek, E. Hancioglu, V. Biolkova, "Current-mode KHN filter employing Current Differencing Transconductance Amplifiers", *AEU – Int. Journal of Electronics and Communications*, vol. 60, no. 6, pp. 443–446, 2006. [Online]. Available: http://dx.doi.org/10.1016/j.aeue.2005.09.003

[6] W. Jaikla, A. Lahiri, "Resistor-less current-mode four-phase quadrature oscillator using CCCDTAs and grounded capacitors", *AEU – Int. Journal of Electronics and Communications*, vol. 66, no. 3, pp. 214–218, 2012. [Online]. Available: http://dx.doi.org/10.1016/j.aeue.2011.07.001

[7] Ch. Sakul, W. Jaikla, K. Dejhan, "New resistorless current-mode quadrature oscillators using 2 CCCDTAs and grounded capacitors", *Radioengineering*, vol. 20, no. 4, pp. 890–896, 2011.

[8] R. L. Geiger, E. Sanchez-Sinencio, "Active filter design using operational transconductance amplifiers: a tutorial", *IEEE Circ. and Devices Magazine*, vol. 1, pp. 20–32, 1985. [Online]. Available: http://dx.doi.org/10.1109/MCD.1985.6311946

[9] A. Fabre, O. Saaid, F. Wiest, C. Boucheron, "High frequency applications based on a new current controlled conveyor", *IEEE Trans. on Circuits and Systems - I*, vol. 43, no. 2, pp. 82–91, 1996.

[10] A. Sedra, K. C. Smith, "A second generation current conveyor and its applications", *IEEE Trans. Circuit Theory*, vol. CT-17, no. 2, pp. 132–134, 1970. [Online]. Available: http://dx.doi.org/10.1109/TCT.1970.1083067

[11] R. Prokop, V. Musil, "Modular approach to design of modern circuit blocks for current signal processing and new device CCTA", *in Proc. Conf. on Signal and Image Processing IASTED*, Anaheim, 2005, pp. 494–499.

[12] M. Siripruchyanun, W. Jaikla, "Current controlled current conveyor transconductance amplifier (CCCCTA): a building block for analog signal processing", *Electrical Engineering Springer*, vol. 90, no. 6, pp. 443–453, 2008. [Online]. Available: http://dx.doi.org/10.1007/s00202-007-0095-x

[13] R. Sotner, J. Jerabek, R. Prokop, K. Vrba, "Current gain controlled CCTA and its application in quadrature oscillator and direct frequency modulator", *Radioengineering*, vol. 20, no. 1, pp. 317–326, 2011.

[14] A. Lahiri, M. Gupta, "Realizations of grounded negative capacitance using CFOAs", *Circuits, Systems and Signal Processing*, vol. 30, no. 1, pp. 134–155, 2011. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1007/s00034-010-9215-3

[15] A. U. Keskin, C. Aydin, E. Hancioglu, C. Acar, "Quadrature oscillator using current differencing buffered amplifiers (CDBA)", *Frequenz* vol. 60, no. 3, pp. 21–23, 2006.

[16] B. Linares-Barranco, A. Rodriguez-Vazquez, E. Sanches-Sinencio, J. L. Huertas, "CMOS OTA-C high-frequency sinusoidal oscillators", *IEEE Journal of Solid-State Circuits*, vol. 26, no. 2, pp. 160–165, 1991. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1109/4.68133

[17] Y, Tao, J. K. Fidler, "Electronically tunable dual-OTA second order sinusoidal oscillators/filters with non-interacting controls: A systematic synthesis approach", *IEEE Trans. on Circuits and Systems - I*, vol. 47, no. 2, pp. 117–129, 2000.

[18] Y. Li, "Electronically tunable current-mode quadrature oscillator using single MCDTA", *Radioengineering*, vol. 19. no. 4, pp. 667–671, 2010.

[19] R. Keawon, W. Jaikla, "A Resistor-less current-mode quadrature sinusoidal oscillator employing single CCCDTA and grounded capacitors", *Przeglad Elektrotechniczny*, vol. 87, no. 8, pp. 138–141. 2011.

[20] N. Pandey, S. K. Paul, "Single CDTA-based current mode all-pass filter and its applications", *Journal of Electrical and Computer Engineering,* vol. 2011, pp. 1–5, 2011.

[21] S. N. Songkla, W. Jaikla, "Realization of electronically tunable current-mode first-order allpass filter and its application", *Int. Journal of Electronics and Electrical Engineering*, vol. 2012, no. 6, pp. 40–43, 2012.

[22] S. Minaei, E. Yuce, "Novel voltage-mode all-pass filter based on using DVCCs", *Circuits Systems and Signal Processing*, vol. 29, no. 3, pp. 391–402, 2010. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1007/s00034-010-9150-3

[23] N. Herencsar, J. Koton, K. Vrba, A. Lahiri, "New voltage-mode quadrature oscillator employing single DBTA and only grounded passive elements", *IEICE Electronics Express*, vol. 6, no. 24, pp. 1708–1714, 2009. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1587/elex.6.1708

[24] J. W. Horng, "A sinusoidal oscillator using current-controlled current conveyors", *Int. Journal of Electronics*, vol. 88, no. 6, pp. 659–664, 2001. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1080/00207210110044369

[25] A. Lahiri, "A. Novel voltage/current-mode quadrature oscillator using current differencing transconductance amplifier", *Analog Integrated Circuits and Signal Processing*, vol. 61, no. 2, pp. 199–203, 2009. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1007/s10470-009-9291-0

[26] S. I. Liu, "Single-resistance-controlled/ voltage-controlled oscillator using current conveyors and grounded capacitors", *Electronics Letters*, vol. 31, no. 5, pp. 337–338, 1995. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1049/el:19950259

[27] M. T. Abuelmaatti, M. H. Khan, "New electronically-tunable oscillator circuit using only two OTAs", *Active and Passive Electronic Components*, vol. 20, no. 4, pp. 189–194, 1998. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1155/1998/63168

[28] S. Maheshwari, B. Chatuverdi, "High output impedance CMQOs using DVCCs and grounded components", *Int. Journal of Circuit Theory and Applications*, vol. 39, no. 4, pp. 427–435, 2011. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1002/cta.636

[29] S-H. Tu, Y-S. Hwang, J-J. Chen, A. M. Soliman, C-M. Chang, "OTA-C arbitrary-phase-shift oscillators", *IEEE Trans. on Instrumentation and Measurement*, vol. 61, no. 8, pp. 2305–2319, 2012. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1109/TIM.2012.2184958

[30] M. Kumngern, J. Chanwutium, K. Dejhan, "Electronically tunable multiphase sinusoidal oscillator using translinear current conveyors", *Analog Integrated Circuits and Signal Processing*, vol. 65, no. 2, pp. 327–334, 2010. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1007/s10470-010-9470-z

[31] V. Biolkova, J. Bajer, D. Biolek, "Four-phase oscillator employing two active elements", *Radioengineering*, vol. 20, no. 1, pp. 334–339, 2011.

[32] N. Herencsar, S. Minaei, J. Koton, E. Yuce, K. Vrba, "New resistorless and electronically tunable realization of dual-output VM all-pass filter using VDIBA", *Analog Integrated Circuits and Signal Processing*, vol. 74, no. 1, pp. 141–154, 2013. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1007/s10470-012-9936-2

[33] R. Sotner, N. Herencsar, J. Jerabek, J. Koton, T. Dostal, K. Vrba, "Electronically controlled oscillator with linear frequency adjusting for four-phase or differential quadrature output signal generation", *Int. Journal of Circuit Theory and Applications*, 2013. (in press) [Online]. Available: [Online]. Available: http://dx.doi.org/10.1002/cta.1919

[34] R. Sotner, Z. Hrubos, N. Herensar, J. Jerabek, T. Dostal, "Precise electronically adjustable oscillator suitable for quadrature signal generation employing active elements with current and voltage gain control", *Circuits Systems and Signal Processing*, vol. 33, no. 1, pp. 1–35, 2014. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1007/s00034-013-9623-2

[35] D. Prasad, D. R. Bhaskar, "Electronically controllable explicit current output sinusoidal oscillator employing single VDTA", *ISRN Electronics*, vol. 2012, pp. 1–5, 2012. [Online]. Available: [Online]. Available: http://dx.doi.org/10.5402/2012/382560

[36] N. Herencsar, R. Sotner, J. Koton, J. Misurec, K. Vrba, "New compact VM four-phase oscillator employing only signle z-copy VDTA and all grounded passive elements", *Elektronika ir Elektrotechnika*, vol. 19, no. 10, pp. 87–90, 2013.

[37] R. Sotner, A. Lahiri, J. Jerabek, N. Herencsar, J. Koton, T. Dostal, K. Vrba, "Special type of three-phase oscillator using current gain control for amplitude stabilization", *Int. Journal of Physical Sciences*, vol. 7, no. 25, pp. 3089–3098, 2012.

[38] R. Sotner, J. Jerabek, N. Herencsar, "Voltage differencing buffered/ inverted amplifiers and their applications for signal generation", *Radioengineering*, vol. 22, no. 2, pp. 490–504, 2013.

[39] R. Sotner, N. Herencsar, J. Jerabek, R. Prokop, A. Kartci, T. Dostal, K. Vrba, "Z-Copy controlled-gain voltage differencing current conveyor: Advanced possibilities in direct electronic control of first-order filter", *Elektronika ir Elektrotechnika*, vol. 20, no. 6, pp. 77–83, 2014.