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Novel Oscillator Based on Voltage and Current-Gain Adjusting Used for Control of Oscillation Frequency and Oscillation Condition

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***Abstract*—The paper deals with novel controllable oscillator where two types of electronic control are used. Proposed second-order circuit contains current follower, adjustable current amplifier, adjustable voltage amplifier, two resistors and two grounded capacitors. Oscillation frequency is tuned by voltage gain of used voltage amplifier that is represented by high-frequency voltage-mode multiplier. Oscillation condition is automatically regulated by current gain of the adjustable current amplifier which is based on current-mode multiplier. Experimental results confirmed workability of the circuit.**

***Index Terms*—Electronic control, oscillator, adjustable current amplifier, current follower/inverter, adjustable voltage amplifier.**

I. INTRODUCTION

Many active elements which are suitable for electronic control could be found in open literature [1]. Several ways how to control parameters of applications have been described [2]–[9]. Surakamponton et al. [2] and Fabre et al. [3] introduced active elements with possibility of current gain control. This active element is referred to as electronically controllable current conveyor of second generation (ECCII) and it allows adjusting of current transfer between current input and current output of the current conveyor [1], [4], [5]. Another way of control is change of transconductance [1], [6] by bias current. Geiger et al. [6] described several basic applications of transconductors (OTAs) and formulated background of knowledge in this topic. Fabre et al. [7] presented active element with different possibility of control. The biasing current in internal structure of the current conveyor was used for control of intrinsic resistance of current input. Minaei et al. [8] proposed ECCII with combination of two methods of control in one device (intrinsic resistance and current gain). Marcellis et al. [9] implemented control of the current and voltage gains. Digital potentiometers are popular solutions for control of applications with standard voltage opamps at low frequencies (hundreds of kHz maximally) because their frequency features are not satisfactory in this particular case. Methods how to control frequency of oscillation (FO) and condition of oscillation (CO), that were sketched out, are discussed in more detail in the following text. All discussed ways of control suppose direct electronic adjusting in frame of parameter of active element. Other ways which use passive elements (resistors in many cases) and their replacements (FETs, digital potentiometers, ...) belong to group of indirect methods.

The first group of oscillator solutions employs controllable tranconductances (g_m). In the past, only simple transconductors (voltage controlled current sources) with differential input and single output were used. Rodriguez-Vazques et al. [10], Linarez-Barranco et al. [11], [12], Senani [13], Abuelmaatti [14] and many others presented simple and flexible solutions using at least two transconductors. Over the years, transconductor conceptions have been improved and also novel modified types were developed. Biolek [15], [16] introduced so-called current differencing transconductance amplifier (CDTA), where current differencing unit at the input of transconductor is used. Lahiri [17] proposed controllable oscillator with two CDTAs and two grounded capacitors or oscillator employing only one active element [18], [19]. Three CDTAs

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were used by Tangsrirat et al. in [20]. Solutions of third order oscillators were also investigated. Horng [21], [22] built oscillator with three grounded capacitors. Prasad et al. [23] utilized novel approach in oscillator with one multiple-output current controlled current differencing transconductance amplifier (MO-CCCDTA).

TABLE I. COMPARISON OF IMPORTANT PREVIOUSLY REPORTED CONTROLLABLE OSCILLATORS

Work	Active element	No. of active/passive elements	Simple equations for FO / CO	AGC proposed	FO range	THD	Type of FO / CO control	DC voltage control of FO
[11]	OTA	4 / 3	YES / YES	YES	3-10.3 MHz	0.2 %	g_m / g_m	NO (I_b)
[12]	OTA	2-4 / 2-4	NO / NO	YES	12-56 MHz	2.5 %	g_m / g_m	NO (I_b)
[13]	OTA	3 / 2	YES / YES	N/A	N/A	N/A	g_m / g_m	NO (I_b)
[14]	OTA	2 / 3	YES / YES	N/A	N/A (300 kHz)*	N/A	g_m / R	NO (I_b)
[16]	CDTA	2 / 6	YES / YES	N/A	N/A (1 MHz)*	N/A	R / R, g_m	NO
[17]	CDTA	2 / 3	YES / YES	N/A	N/A (10 MHz)*	N/A	g_m / R, g_m	NO (I_b)
[18]	CCTA	1 / 4	YES / YES	N/A	21-682 kHz	N/A	g_m / R	NO (I_b)
[19]	DVCCTA	1 / 4	YES / YES	N/A	20-700 kHz	4.6 %	g_m / R	NO (I_b)
[20]	CDTA	3 / 2	YES / YES	N/A	0.2-1.8 MHz	2.5 %	g_m / g_m	NO (I_b)
[21]	CDTA	3 / 3	YES / NO	N/A	3-9 kHz	1 - 2.6 %	g_m / g_m	NO (I_b)
[22]	CDTA	3 / 3	YES / YES	N/A	0.4-0.8 MHz	10 %	g_m / g_m	NO (I_b)
[23]	MO-CCCDTA	1 / 3	YES / YES	N/A	N/A (114 kHz)*	0.6 %	g_m / R	NO (I_b)
[26]	CCCDTA	2 / 2	YES / YES	N/A	0.1-5 MHz	N/A	g_m / R_X	NO (I_b)
[27]	CCCDTA	2 / 2	YES / YES	YES	1-4 MHz	1.6 %	g_m / R_X	NO (I_b)
[28]	CCCII	2 / 2	YES / YES	N/A	0.1-1.7 MHz	1 - 7 %	R_X / B	NO (I_b)
[29]	ZC-CG-CDBA	2 / 5	YES / YES	YES	0.25-2.75 MHz	0.2 %	B_G / R	NO (digital)
[30]	CCTA	1 / 4	YES / YES	N/A	0.25-1.23 MHz	0.6 - 4 %	B_G / R	YES
[31]	DT, CA	3 / 4	YES / NO	N/A	0.6-2.2 MHz	0.4 - 0.9 %	B_G / R	YES
[32]	ECCII-, CCII+	3 / 5	YES / YES	N/A	0.26-1.25 MHz	0.2 - 1.5 %	B_G / B_G	YES
[33]	CG-CIBA/CFBA	2 / 5	YES / YES	YES	0.1-1.26 MHz	0.6 - 1.3 %	B_G / B_G	YES
[34]	PCA	3 / 4	YES / YES	N/A	50-300 kHz	N/A	B_G / B_G	NO (I_b)
Prop.	VA, CA, MO-CF/I	3 / 4	YES / YES	YES	12-25.5 MHz	0.3 - 2 %	A_G / B_G	YES

Notes (parameters and abbreviations which are not explained in text of the introductory section):
I_b - bias current (type of control)
g_m / g_m - two different transconductances are used for independent FO and CO control
g_m / R - transconductance suitable for FO and resistance value for CO control
R / R, g_m - resistance value(s) suitable for FO control and resistance or/and transconductance suitable for CO control
g_m / R, g_m - two different transconductances and also one transconductance and resistance are suitable for independent FO and CO control
g_m / R_X - transconductance suitable for FO and electronically controllable intrinsic resistance suitable for CO control
B_G / R - current gain suitable for FO and resistor value for CO control
B_G / B_G - two different current gains are used for independent FO and CO control
A_G / B_G - voltage gain suitable for FO and current gain for CO control
CCCDTA - current controlled CDTA; DVCCTA - differential voltage CCTA; CCCII - current controlled (translinear) current conveyor of second generation; CA - current amplifier (controllable); VA - voltage amplifier (controllable); MO-CF/I - multi-output current follower/inverter; DT - diamond transistor; CG-CIBA/CFBA - controlled gain current inverted buffered amplifier / current follower buffered amplifier
N/A - not possible, not available or not verified
* verified only at stable FO (discrete value sets)

The second group consists of oscillators which are controllable by adjustable intrinsic resistance of current input (R_X) in novel modified active elements. Current conveyor transconductance amplifier (CCTA) introduced by Prokop et al. [24] was also frequently used in adjustable oscillators. Siripruchyanun et al. [25] introduced possibility of R_X control and its usefulness in applications together with g_m adjusting. The CDTA element was also extended and controllable R_X and g_m parameters were determined for control of resistor-less oscillator by Jaikla et al. [26]. Similar oscillator was proposed also by Sakul et al. in [27]. The third group contains solutions employing adjusting of the current gain (B_G) in order to control the application. Kumngern et al. implemented combination of two methods, i.e. control of R_X and current gain (B_G) for adjusting of FO and CO in [28]. Biolek et al. [29] proposed oscillator with so-called z-copy controlled-gain current differencing buffered amplifier (ZC-CG-CDBA) where they also implemented possibility of current gain adjusting. Several applications of adjustable current gain were also discussed in [30]–[33]. Herencsar et al. [34] introduced programmable current amplifier (PCA, DACA) [35] and its application in oscillator.

Several solutions of the controllable oscillators based on above discussed methods are compared in Table I. Following problems of the discussed results are evident: I. some solutions require larger number of passive elements [12], [16], [29], [32], [33]; II. only few works deal with applications that operate in frequency range above 10 MHz [11], [12], [17]; III. many solutions were designed as tunable (or have these abilities), but their verification was not provided [13], [14], [16], [17], [23]; IV. some variants suffer from high total harmonic distortion (THD) [19], [22], [28], [30]; V. automatic gain control (AGC) for amplitude stabilization was proposed in minimum conceptions [11], [12], [27], [29], [33]; VI. additional conversion of DC control voltage to bias current (controlling g_m for example) is required [11]–[28], [34]; VII. in some cases equations for FO or CO are complicated - matching of several parameters (equality of several C or g_m) required for electronic control [12], [21], [31]; VIII. intrinsic resistance (R_X) is generally nonlinear temperature dependent parameter and intended control by R_X [25]–[28] may cause problems for higher amplitudes of processed signals in some applications; IX.

some solutions require controllable replacement of passive resistor to control of CO [16], [18], [19], [23], [29]–[31].

We prepared a solution that solves several above discussed problems simultaneously. Independent direct electronic control of FO and CO by adjustable voltage and current gain that was not discussed in hitherto published works is used in our approach. Advantages (fulfilled together) of proposed circuit are: I. direct electronic DC voltage control of FO allows comfortable driving from digital systems; II. simple oscillation condition suitable for direct electronic control; III. approach based on high-speed voltage- and current-mode multipliers (used as behavioral representation of active elements) allows operation range in tens of MHz; IV. precise AGC allows sufficient THD in adjusted frequency range; V. we avoid the R_X control (for adjustable purposes) in this work; VI. CO is directly controllable by parameters of active element (no replacement of resistor is required). When on-chip implementation is performed, one resistor with low value is "absorbable" to the current input intrinsic resistance. Of course, other simpler circuits (Table I), controlled by several different ways exist, but above listed features are not fulfilled simultaneously in many of discussed solutions.

II. PROPOSED OSCILLATOR

The basic principle of active elements (adjustable voltage amplifier, adjustable current amplifier and current distributor - current follower/inverter) is explained in Fig. 1.

We implemented two integrator loops with controllable current feedback in order to design simple type of the adjustable oscillator with minimum passive elements and grounded capacitors. Possibility of current and voltage gain control is very useful for tuning of FO and control of CO in our solution that is shown in Fig. 2. Basic component of the signal flow graph (SFG) is the current follower and inverter (MO-CF/I). Combined arrows substitute voltage to current (open-closed) and current to voltage (closed-open) conversion in Fig. 2(a).

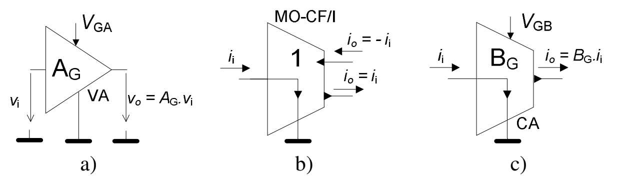


Fig. 1. Active elements applied in proposed oscillator: a) adjustable voltage amplifier, b) current distributor c) adjustable current amplifier.

We can briefly explain principle of the circuit in Fig. 2(b). The node 1, where three passive elements are connected together, is the most important part. These elements form significant impedance (conversion constant between current and voltage). Voltage in node 1 is transformed to the current through R_1. The MO-CF/I produces identical copies of its input current (inverting or non-inverting output). Negative output is connected to C_2, where current is changed to voltage (node 2). This voltage is amplified or attenuated by adjustable voltage amplifier (VA) with voltage gain A_G. Finally, the output voltage of the VA is transferred through divider (R_1, R_2) with capacitive load (C_1). The second loop (S_2) contains current amplifier (CA) with the current gain B_G and it is connected directly to positive output of the MO-CF/I. The CA represents the feedback path which is connected back to the node 1. Output current of the CA is transformed from current to voltage at the impedance formed by R_1, R_2 and C_1.

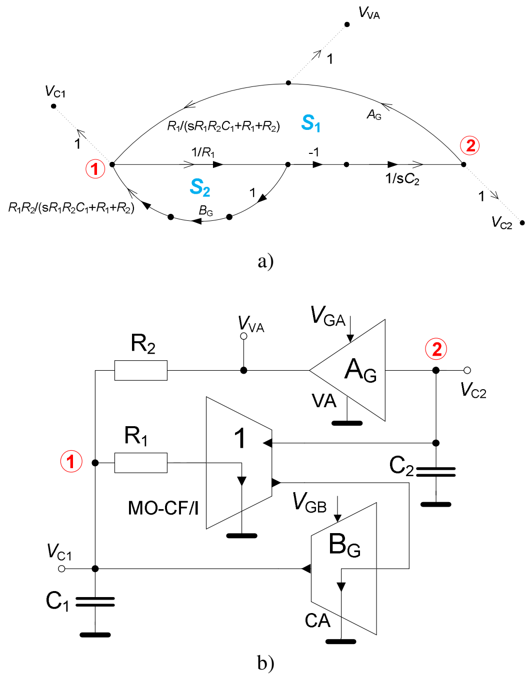


Fig. 2. Proposed oscillator: a) SFG for explanation; b) circuit representation.

Analysis of the SFG in Fig. 2 (by Mason rule [36], [37]) yields to following characteristic equation

$$\Delta = 1-(S_1+S_2)=$$
$$=1-\left[\frac{-A_G}{sR_1C_2}\left(\frac{R_1}{sR_1R_2C_1+R_1+R_2}\right)+\frac{B_G}{R_1}\left(\frac{R_1R_2}{sR_1R_2C_1+R_1+R_2}\right)\right]=$$
$$=s^2+\frac{R_1+R_2-B_GR_2}{R_1R_2C_1}s+\frac{A_G}{R_1R_2C_1C_2}=0. \quad (1)$$

We can determine CO and FO as follows:

$$B_G \geq 1+\frac{R_1}{R_2}, \quad (2)$$

$$\omega_0=\sqrt{\frac{A_G}{R_1R_2C_1C_2}}. \quad (3)$$

It is obvious that CO is controllable by B_G and FO by A_G and they are mutually independent. The relative sensitivities of FO on values of passive elements and gains, that are evident from (3), are:

$$S_{A_G}^{\omega_0}=-S_{R_1}^{\omega_0}=-S_{R_2}^{\omega_0}=-S_{C_1}^{\omega_0}=-S_{C_2}^{\omega_0}=0{,}5, \quad (4)$$

$$S_{B_G}^{\omega_0}=0. \quad (5)$$

III. REAL IMPLEMENTATION AND EXPERIMENTAL VERIFICATION

We created non-ideal model of the proposed circuit from Fig. 2(b). Additional nodal impedances that are caused by real active elements and additional voltage buffers for impedance separation were added. Complete model is shown in Fig. 3. We implemented commercially available active elements for experimental verifications. The MO-CF/I element was implemented by EL4083 [38] current mode multiplier. The current amplifier (CA) with adjustable current gain is represented by EL2082 [39] current mode multiplier. We constructed adjustable voltage amplifier from high frequency voltage mode multiplier AD834 [40] and high speed opamp AD8045 [41].

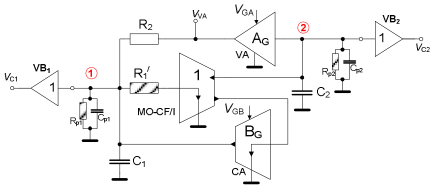


Fig. 3. Analysis of parasitic influences of proposed oscillator.

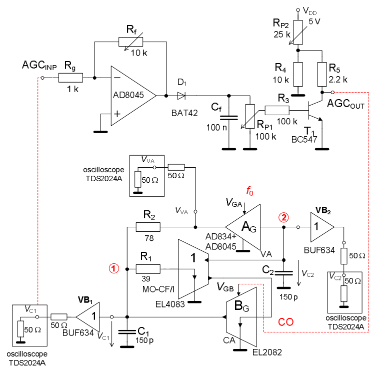
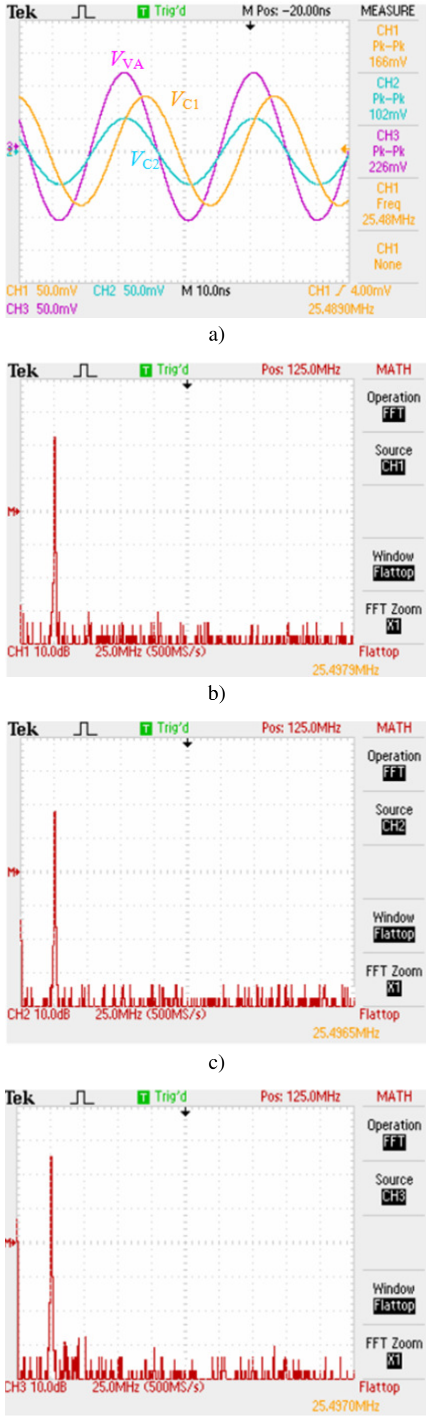


Fig. 4. Measuring setup for experimental tests.

Additional (separation) buffers were BUF634 types [42]. We selected values of passive elements as follows: $R_1 = 39\ \Omega$ (real input resistance of MO-CF/I is considered), $R_2 = 78\ \Omega$, $C_1 = C_2 = C = 150$ pF, $B_G = 2$. Important parameters of the MO-CF/I (EL4083 [38]) are output impedances, both are characterized by $R_{out\_MO\text{-}CF} \approx 1$ MΩ/ $C_{out\_MO\text{-}CF} \approx 5$ pF and also input resistance, $R_{inp\_MO\text{-}CF} \approx 40\ \Omega$. Producer of EL2082 (modeling CA) indicates output properties as follows: $R_{out\_CA} \approx 1$ MΩ/ $C_{out\_CA} \approx 5$ pF, $R_{inp\_CA} \approx 95\ \Omega$. We suppose that influence of R_{inp_CA} is negligible because $R_{inp\_CA} << R_{out\_MO\text{-}CF}$. The voltage amplifier (VA) is characterized by input resistance $R_{inp\_VA} \approx$ 25 kΩ (AD834). High speed VA was built in accordance with recommendations in [40]. Output resistance of VA is negligible (datasheet of AD8045 shows value < 4 Ω up to 100 MHz). Input impedance of additional separation voltage buffer is $R_{inp\_VB} \approx 8$ MΩ/ $C_{inp\_VB} \approx 8$ pF (BUF634). Outputs of the MO-CF/I are dominant in the node 1 where $R_{p1} \approx R_{out\_CA} \| R_{inp\_VB} \approx 890$ kΩ and $C_{p1} \approx C_{out\_CA} + C_{inp\_VB} \approx$ 13 pF.

The main problem is in the node 2, because input resistance of VA (AD834) is only 25 kΩ i.e. $R_{p2} \approx R_{inp\_VA} \| R_{out\_MO\text{-}CF} \| R_{inp\_VB} \approx 24$ kΩ. Capacitances in the node 2 have overall values $C_{p2} \approx C_{inp\_VA} + C_{out\_MO\text{-}CF} + C_{inp\_VB} \approx 18$ pF. Value of R1 is also influenced by $R_{inp\_MO\text{-}CF} \approx 40\ \Omega$, i.e. real $R_1' \approx R_1 + R_{inp\_MO\text{-}CF} \approx 79\ \Omega$. We can include parasitic capacitances to "working" values as $C_1' \approx C_1 + C_{p1} \approx 163$ pF, $C_2' \approx C_2 + C_{p2} \approx 168$ pF. However, estimation of parasitic features given by printed circuit board (PCB) is very problematic.



a)

b)

c)

d)

Fig. 5. Experimental results for f_0 = 25.5 MHz, A_G = 4: a) all transient responses, b) spectrum of V_{C1}, c) spectrum of V_{C2}, d) spectrum of V_{VA}.

Analysis of parasites in circuit in Fig. 3 leads to more real forms of CO and FO:

$$B_G' \geq \frac{R_1'R_2R_{p1}C_1' + R_2R_{p1}R_{p2}C_2' + R_1'R_2R_{p2}C_2' + R_1'R_{p1}R_{p2}C_2'}{R_2R_{p1}R_{p2}C_2'}, \quad (6)$$

$$\omega_0' = \sqrt{\frac{A_GR_{p1}R_{p2} + R_1'R_2 + R_{p1}R_2 + R_{p1}R_1' - B_G'R_{p1}R_2}{R_1'R_2R_{p1}R_{p2}C_1'C_2'}}. \quad (7)$$

The term $A_GR_{p1}R_{p2}$ in (7) has more than hundred times higher value than term $B_G'R_{p1}R_2$ for $B_G = 2$ and $A_G > 1$.

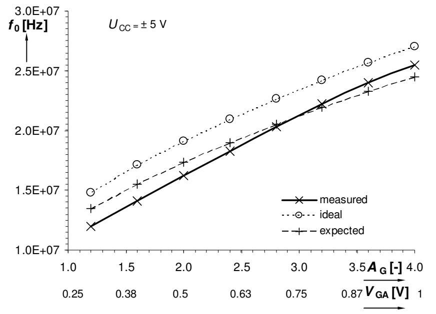


Fig. 6. Measured dependence of FO on A_G.

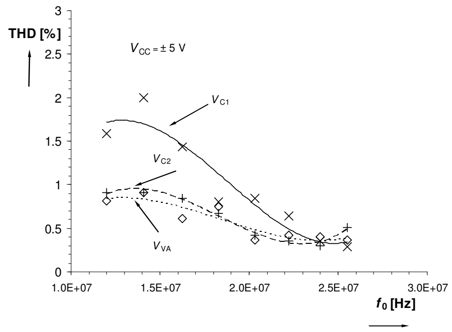
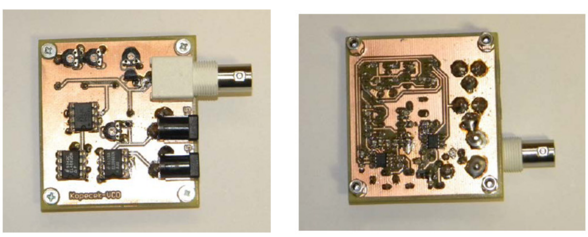


Fig. 7. Measured dependence of THD on FO.

Therefore, its influence on FO is insignificant. Nevertheless, significant effects appear for lower A_G (<< 1). This drawback increases with lower value of R_{p2} (R_{p1} >> R_{p2} in our equivalent circuit model). It is caused by specific feature of used VA. The next important problem is quite high value of C_{p2}.

We tested proposed circuit in laboratory and find out the following results. The oscillator was modified (supplemented by automatic gain control circuit - AGC for amplitude stabilization, impedance matching) and carefully adjusted for adequate operation. The tested device was connected to measuring installation included in Fig. 4. Additional opamp in the AGC loop (pre-amplification) was necessary because output level of VB_1 is quite low (about 100 mV_{P-P}) for sufficient THD (AD834 has restricted linear dynamical range of input voltage) and does not reach threshold voltage of the diode in the rectifier. Time domain results and spectral analyses for the highest achieved FO are shown in Fig. 5.



a) b)

Fig. 8. Measured prototype: a) top side, b) bottom side.

The dependence of FO on A_G is depicted in Fig. 6. Ideal range (when only $R_{inp\_MO\text{-}CF}$ is included) of FO tuning was calculated between 14.81 and 27.05 MHz. Expected range (calculation from (7)) of FO control is from 13.43 to 24.52 MHz. Measurements provided range from 12.01 to 25.50 MHz. All results were obtained for A_G adjusted from 1.2 to 4. THD was evaluated as 0.3 to 2% (Fig. 7). Measured prototype is shown in Fig. 8.

IV. CONCLUSIONS

Presented work shows that two different ways of control (voltage and current gain) are also possible for tunable oscillator in comparison to classical method based on change of resistor(s) value or standard methods of electronic control by transconductance (g_m) [10]–[23], intrinsic resistance [7], [8], [25] or their combination [26], [27] for example. Researchers try to find alternative methods of control of FO and CO (as we can see in [29]–[35]). Such methods may avoid using some not-generally advantageous ways of direct electronic control of parameters (control of intrinsic resistance R_X for example). Presented solution is also an attempt, which shows how to avoid necessity of R_X control in mixed-mode applications utilizing current-mode active elements (compared to [26]–[28]).

Presented solution has several conveniences that are not fulfilled in many above compared solutions (Table I) simultaneously. Main advantages of the proposed solution are: I. direct simple DC voltage control of FO; II. simple and specially established CO - easy implementation of AGC by DC control voltage (no replacement of passive resistor is required); III. proposal of precise AGC system, which ensures sufficient THD level (0.3 - 2 %) in intended frequency range; IV. additional simplification for on-chip implementation - one resistor (R_1) is "absorbable" to fixed value of intrinsic resistance of current input; V. no additional conversion of control voltages to bias current etc. is required - DC voltage is directly available to adjust the oscillator from control part or other device; VI. due to the high-frequency devices and low values of passive elements, operational range of FO adjusting was at frequencies of several tens of MHz (between 12 - 25.5 MHz). In real case, an attention to sufficient values of nodal impedances (resistances and capacitances) and undesirable couplings must be given.

Active elements were modeled by commercially available current multipliers, voltage amplifiers and buffers. This approach allows preliminary laboratory tests. The authors believe that if the circuit built from discrete commercially available elements works well, then appropriate and future on-chip implementation will work even better.

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