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Current feedback op-amp based linear voltage-controlled oscillator using analog multipliers and minimum passive components

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Multiplier.

Abstract. This paper reports a new realization of linear Voltage-Controlled Oscillator (VCO) using three Current-Feedback Op-Amps (CFOAs), three analog multipliers, and only four passive components. Thus, minimum numbers of passive components are used to devise a canonic sinusoidal oscillator. The circuit provides non-interactive electronic tuning of both the Condition of Oscillation (CO) and the Frequency of Oscillation (FO) via the gains of two different analog multipliers. The impedance at output node exhibits low impedance which is easy to directly connect to load without any additional voltage buffer. The proposed circuit has been simulated in SPICE using macro-model of AD844 CFOA ICs and AD633 multiplier ICs.

1. Introduction

Single-Resistance-Controlled Oscillators (SRCOs) have been researched extensively using a variety of active devices in the recent past. Their popularity is mainly attributed to their independent tuning law for the Condition of Oscillation (CO) and the Frequency of Oscillation (FO). In the last decade, the SRCOs, using electronically controllable active devices like the Differential Voltage Current Conveyor Transconductance Amplifier (DVCCTA) [1], the Differential Voltage Current-Controlled Conveyor Transconductance Amplifier (DVCCCTA) [2], Current Controlled Current Differencing Transconductance Amplifiers (CCCDTAs) [3,4], have been proposed. However, these active devices are not commercially available. Among the wide variety of active devices, by which SRCO realizations have been attempted, Current Feedback Op-Amps (CFOAs) remains as one of the most popular choices for the active device. This is because:

(i) CFOAs have many advantages over conventional op-amps, e.g. wide bandwidth independent of the close-loop gain, high slew-rate, and ease of realizing variety of circuit solutions using a reduced number of passive components [5];
(ii) of their commercial availability, e.g. AD844 [6], making them suitable for bread-board implementations;
(iii) Some commercially available CFOAs, like AD844AN with an externally accessible high-output impedance compensation pin, have been found to be particularly attractive in creating current-mode circuits and particularly Explicit-Current-Output (ECO) oscillators [7-11].

Several SRCOs using CFOAs have been reported in the

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literature [5,12-14]. The oscillator circuits in [5,12,13] use two CFOAs and five passive components (three resistors and two capacitors) and the CO and FO are controllable via two different resistors. The CFOA-based sinusoidal oscillators in [14] are very excellent circuits. They employ three CFOAs and six passive elements (four resistors and two grounded capacitors). The independent control of both CO and FO through separate resistors is achieved. Also, the influence of parasitic elements in CFOAs will not affect the CO during the FO tuning process. However, these circuits do not directly offer electronic control of either the CO or the FO, but the CO/FO controlling resistor may be replaced by MOSFET-based Voltage-Controlled Resistor (VCR) [15] to offer electronic control. Recently, a systematic technique of converting SRCO into VCO has been reported by Gupta et al. [16], wherein the frequency controlling resistor (in both grounded and floating forms) has been suitably replaced by FET-based VCR of [17]. The SRCOs, wherein grounded frequency controlling resistor was used, could be transformed into VCOs without requiring any additional CFOAs, but the resulting circuits required matched resistors to realize VCR and FO and were highly temperature dependent (e.g., due to the mobility factor of the employed MOSFET, μ being proportional to $T^{-1.5}$). An alternate technique to realize VCO with low temperature dependent FO is to use analog multiplier(s) in the loop so that their multiplier gain terms appear in the CO and FO. In such a case, CO and FO will be independently controllable via the voltage gains of two different analog multipliers, which are ratio of two voltages. Several such realizations are available in the literature and their key features are briefed here:

a. The circuit in [18,19] uses three voltage-op amps, a large number of passive components (fourteen or more), and two or more analog multipliers in the feedback loop to realize VCO with independently controllable CO and FO by multiplier gains. The dependence of FO on the control voltage (V_c) for the circuit in [18] is of the form FO being proportional to $\sqrt{V_c}$, and for the circuit in [19] is FO being proportional to V_c, i.e. linear VCO;
b. The circuits in [20] require very few components as compared to the previous circuits [18,19]. Employing only one or two voltage op-amps, seven passive components, and two cascaded analog multipliers, the circuits could realize linear VCOs. However, the circuits require matched resistors to realize the Negative Impedance Convertor (NIC) and the CO does not have any electronic control. In addition, the last two oscillator circuits require CO control by capacitor as compared to the resistor in the first two oscillator circuits;
c. The minimal component count linear VCOs in [21] use only one CFOA, two cascaded analog multipliers, and five passive components. As the circuits in [20], the circuits in [21] lack any electronic control for the CO and establish the CO control via capacitors.

In this paper, we propose a new linear VCO with minimum number of passive components (only four) as compared to any of the VCO circuits in [18-21] and with additional feature of independent electronic CO and FO tuning as compared to the linear VCO circuits in [20,21]. This additional feature is at the cost of increased number of active components, namely three CFOAs and three analog multipliers. However, it should be mentioned that this component count is still much less prevalent than linear VCO with independent electronic CO and FO tuning in [19]. The proposed circuit has been simulated in SPICE using advanced macro-model of AD844 CFOA ICs and AD534 multiplier ICs and the results are in correspondence with the theory.

2. Proposed circuit

The proposed VCO circuit is shown in Figure 1. The proposed oscillator consists of three CFOAs, three analog voltage multipliers, two resistors, and two grounded capacitors. Assuming ideal CFOA and multiplier with no parasitic elements and using routine circuit analysis, we get the following characteristic equation:

$$s^2C_1C_2R_1R_2 + sA_2(C_1R_1 + C_2R_2 - A_1C_2R_1) + A_2^2 = 0. \tag{1}$$

Here, A_1 and A_2 are the gains of the first and second analog multipliers. From Eq. (1), the condition of oscillation and frequency of oscillation are written as:

$$\text{CO:} \qquad C_1R_1 + C_2R_2 \leq A_1C_2R_1, \tag{2}$$

and:

$$\text{FO:} \qquad f_0 = \frac{A_2}{2\pi}\sqrt{\frac{1}{C_1C_2R_1R_2}}. \tag{3}$$

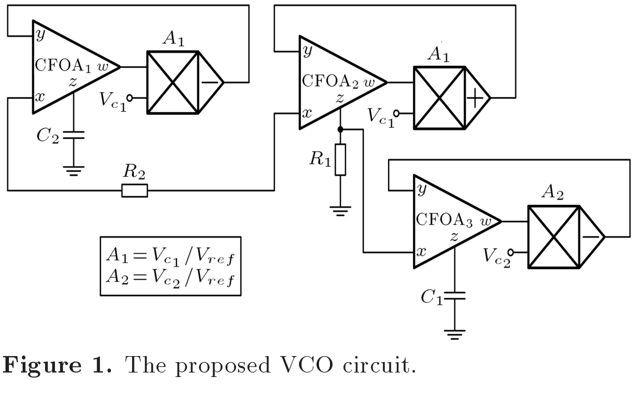


Figure 1. The proposed VCO circuit.

It is evident from Eqs. (2) and (3) that the CO and FO can be independently controlled via the analog multiplier gains, A_1 and A_2, respectively. Also, since FO is proportional to A_2, the circuit is a linear VCO. Now, considering the non-zero parasitic resistance R_x at the x terminal of the CFOA, parasitic resistance R_z and parasitic capacitance C_z at the high-output impedance z terminal of the CFOA, and external resistors R_1, $R_2 << R_z$ (such a condition in most cases is necessarily required to practically realize an oscillator with pseudo de-coupled CO and FO tuning laws [21]), we find the modified FO as:

$$\text{FO:}\quad f_0' = \frac{A_2}{2\pi}\sqrt{\frac{R_2}{(C_1+C_z)(C_2+2C_z)R_1(R_2+R_x)^2}}, \tag{4}$$

and:

$$\text{FO:}\quad f_0' \approx f_0\left[1-\left(\frac{C_z}{2C_1}+\frac{C_z}{C_2}+\frac{R_x}{R_2}\right)\right]. \tag{5}$$

3. Simulation results

The proposed circuit was simulated in SPICE using advanced macro-model of the commercially available CFOA and analog multiplier ICs. AD844 was used as the CFOA IC and AD633 as the analog multiplier IC. The gain of AD633 analog multiplier is $V_c/10$ ($V_{\mathrm{ref}} = 10$ V) [22]. With voltage supplies of ±16 V, passive component values of $C_1 = C_2 = 1nF$, $R_1 = 1$ kΩ, and $R_2 = 5$ kΩ, the CO was set with $A_1 = 1.24$ ($V_{c1} = 12.4$ V) and FO was set with $A_2 = 1$ ($V_{c2} = 10$ V). With these values, the ideal FO according to Eq. (3) would be 71.17 kHz, according to Eq. (4) should be 69.97 kHz (noting that for AD844, $R_x = 50$ Ω, $C_z = 4.5$ pF) and the observed frequency from simulations was 69.01 kHz. The starting and steady-state waveforms of the signal across the w terminal of the second CFOA and its frequency spectrum (magnitude) are shown in Figure 2(a), (b), and (c), respectively. The Total Harmonic Distortion (THD) is about 1.45%. Practically, the THD value could be decreased by setting A_1 close to $(C_1R_1 + C_2R_2)/C_2R_1$. Also, the Automatic Gain Control (AGC) circuit can be used instead of A_1. To investigate the stability of the proposed oscillator, the PSpice Monte-Carlo analysis with 5% Gaussian deviation on capacitors was used. In this study, 100 samples were run for verifying the oscillation frequency. The result is illustrated in Figure 3. It reveals that the proposed oscillator works well against capacitance tolerance.

4. Experimental results

The working of the proposed oscillator was also verified using experimental results. With voltage supplies of ±16 V, passive component values of $C_1 = C_2 = 1$ nF, $R_1 = 1$ kΩ, and $R_2 = 5$ kΩ, the CO was set with $A_1 = 1.228$ ($V_{c1} = 12.28$ V) and FO was set with $A_2 = 1$ ($V_{c2} = 10$). With these values, the ideal FO according to Eq. (3) would be 71.17 kHz; however, the observed frequency from experiment was 62.92 kHz. The steady-state waveforms of the signal across the w terminal of the second CFOA and its frequency spectrum are shown in Figure 4(a) and (b), respectively. The output waveforms and their spectrums for $V_{c2} = 5$ V, 8 V, 11 V, and 13 V are respectively illustrated in Figures 5, 6, 7, and 8. The variation of the FO with V_{c2} is shown in Figure 9.

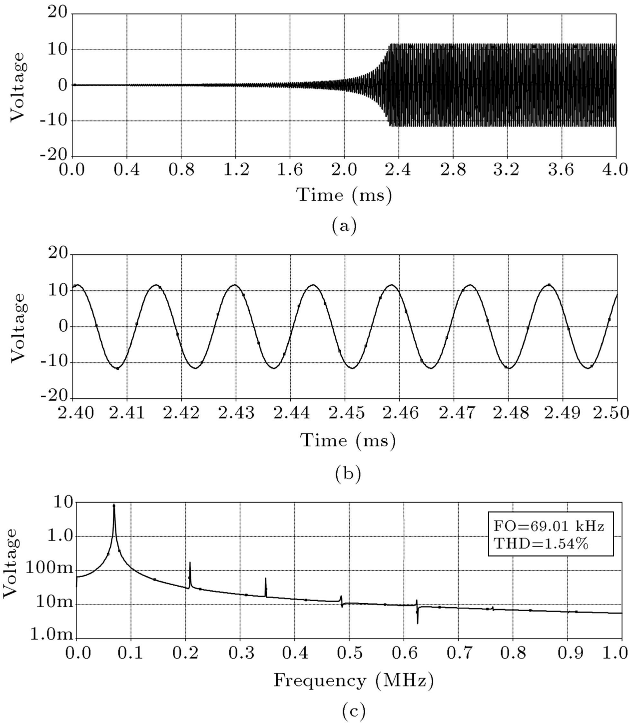
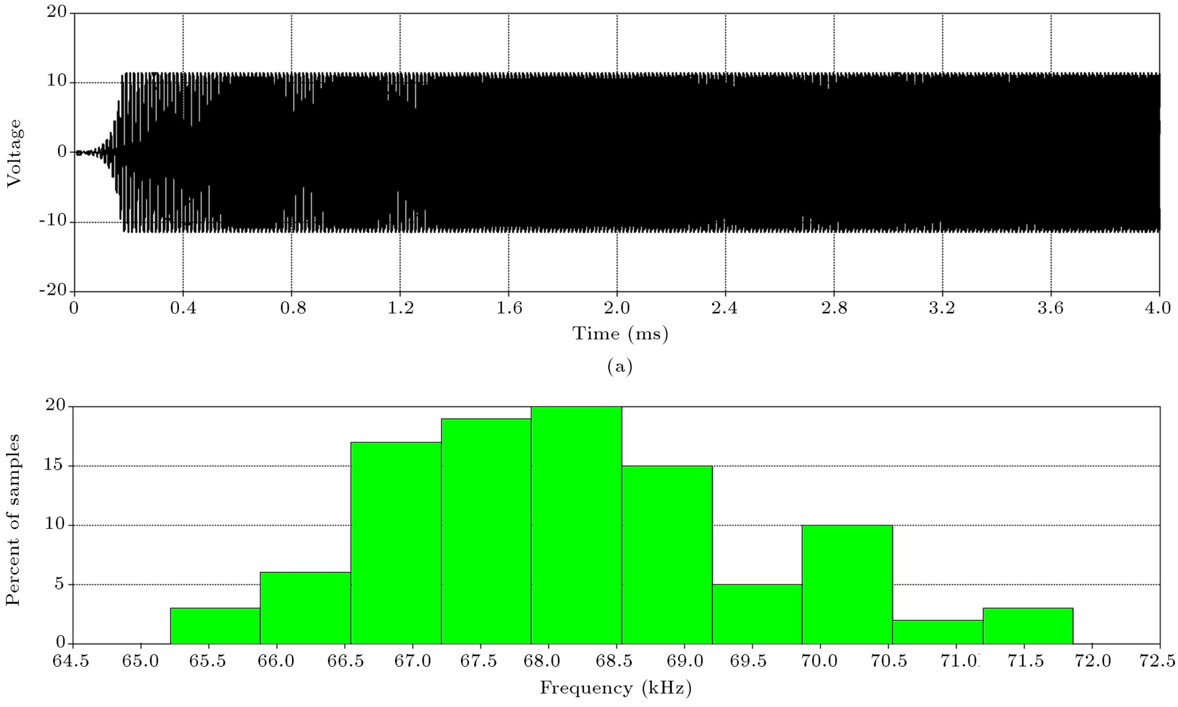


Figure 2. a) Start-up output voltage. b) Steady-state oscillation waveform. c) Frequency Spectrum.

5. Conclusions

We have proposed a new linear VCO, which although employs more active components than those of the linear VCO in [21], it provides independent electronic CO and FO tuning via the gains of the employed analog multipliers. As compared with the linear VCO in [19], which also has independent CO and FO tuning law, our circuit employs reduced number of active and passive components. In fact, our circuit employs minimum number of passive components as compared to any previous VCO in [18-21]. Simulation results using macro-model of commercially available ICs have proved the workability of the proposed circuit. The realizations of VCO with the same features as those in this circuit, but with reduced number of active

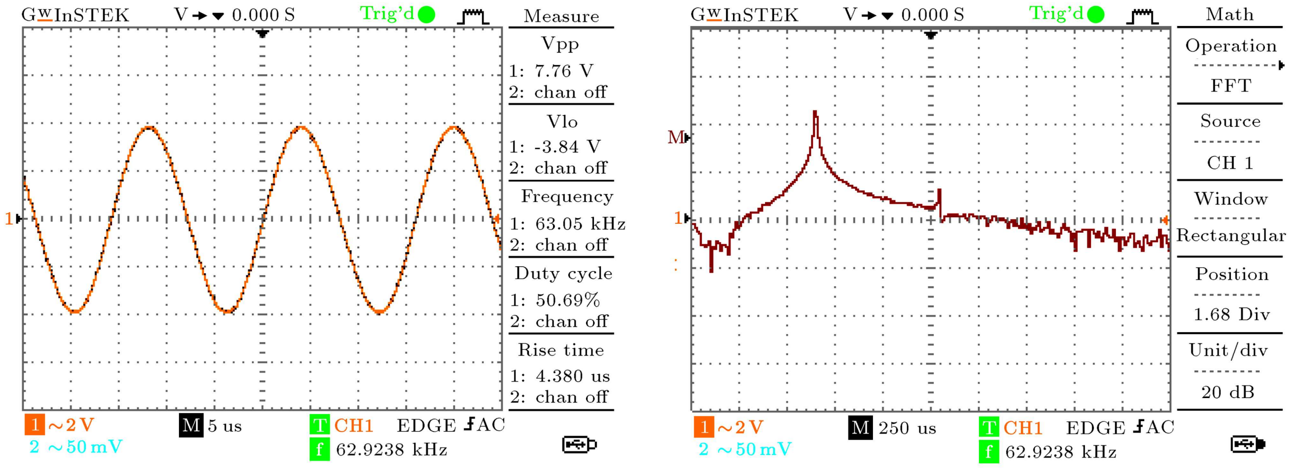


(a)

(b)

n samples=100 n divisions=10	Mean=68158.5 Sigma=1387.92	Minimum=65216 10th %ile=66559	Median=68077.6 90th %ile=70204.2	Maximum=71861.5 3*sigma=4163.77

Figure 3. Monte-Carlo simulation of the proposed oscillator at 5% deviation of capacitance.



(a)

(b)

Figure 4. a) Oscillation waveform. b) Frequency spectrum.

components are a challenging problem which needs to be worked out.

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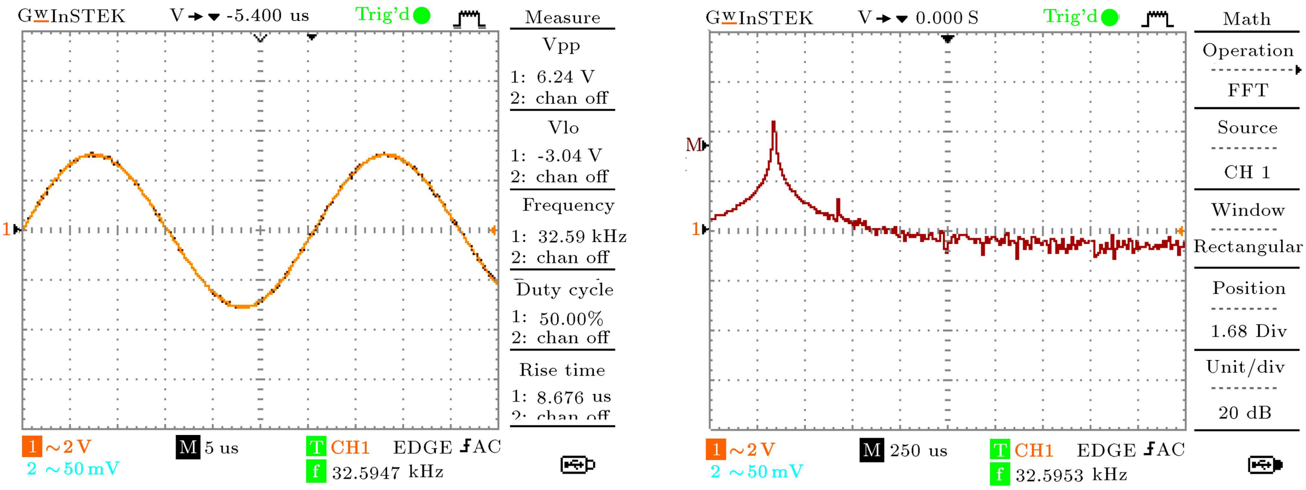
Abbreviations

SRCO	Single-Resistance-Controlled Oscillator;
CO	Condition of Oscillation;
FO	Frequency of Oscillation;

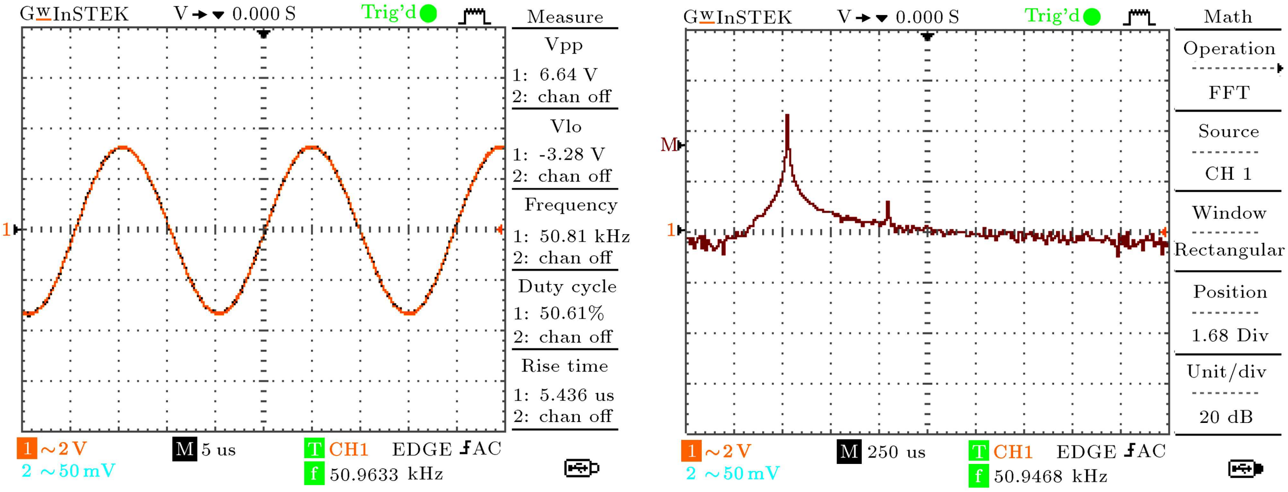


Measure
Vpp
1: 6.24 V
2: chan off
Vlo
1: -3.04 V
2: chan off
Frequency
1: 32.59 kHz
2: chan off
Duty cycle
1: 50.00%
2: chan off
Rise time
1: 8.676 us
2: chan off

Math
Operation
FFT
Source
CH 1
Window
Rectangular
Position
1.68 Div
Unit/div
20 dB

(a) (b)

Figure 5. a) Oscillation waveform. b) Frequency spectrum at $V_{c2} = 5$ V.

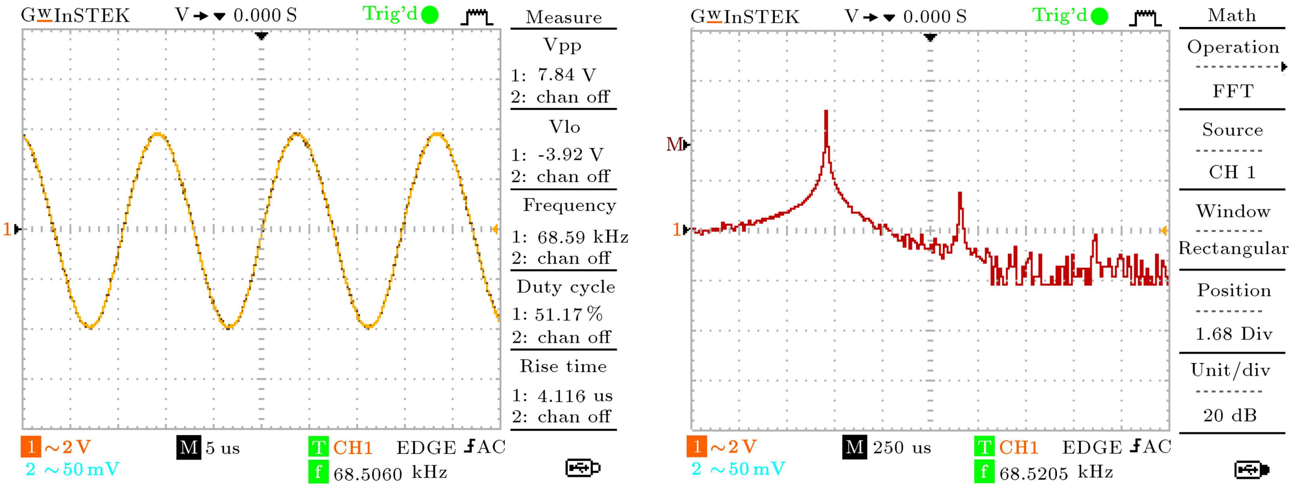


Measure
Vpp
1: 6.64 V
2: chan off
Vlo
1: -3.28 V
2: chan off
Frequency
1: 50.81 kHz
2: chan off
Duty cycle
1: 50.61%
2: chan off
Rise time
1: 5.436 us
2: chan off

Math
Operation
FFT
Source
CH 1
Window
Rectangular
Position
1.68 Div
Unit/div
20 dB

(a) (b)

Figure 6. a) Oscillation waveform. b) Frequency spectrum at $V_{c2} = 8$ V.

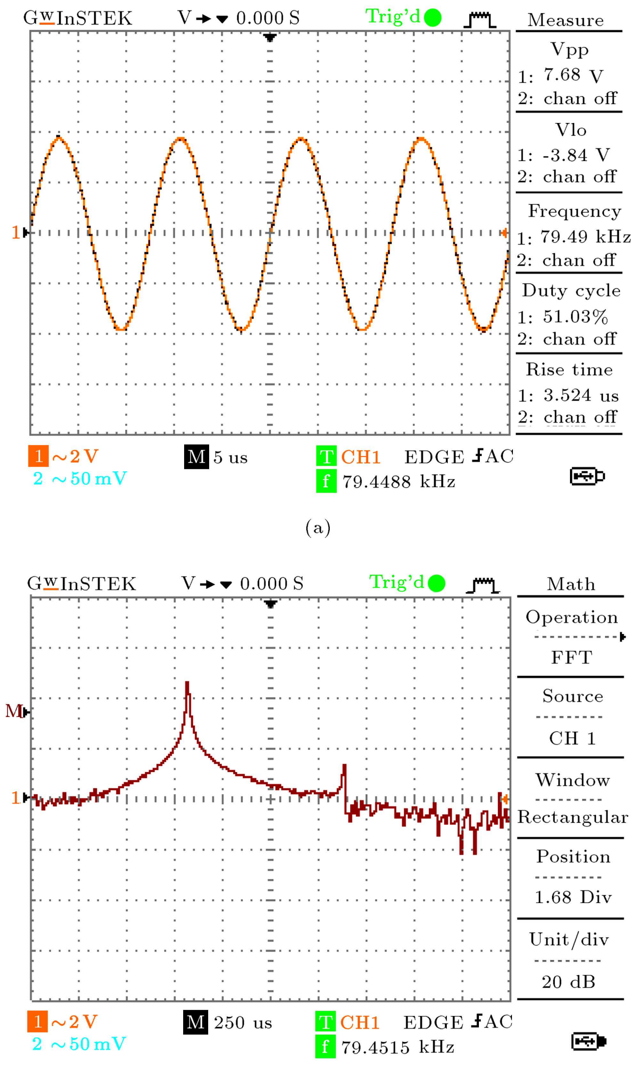


Measure
Vpp
1: 7.84 V
2: chan off
Vlo
1: -3.92 V
2: chan off
Frequency
1: 68.59 kHz
2: chan off
Duty cycle
1: 51.17 %
2: chan off
Rise time
1: 4.116 us
2: chan off

Math
Operation
FFT
Source
CH 1
Window
Rectangular
Position
1.68 Div
Unit/div
20 dB

(a) (b)

Figure 7. a) Oscillation waveform. b) Frequency spectrum at $V_{c2} = 11$ V.



(a)

(b)

Figure 8. a) Oscillation waveform. b) Frequency spectrum at $V_{c2} = 13$ V.

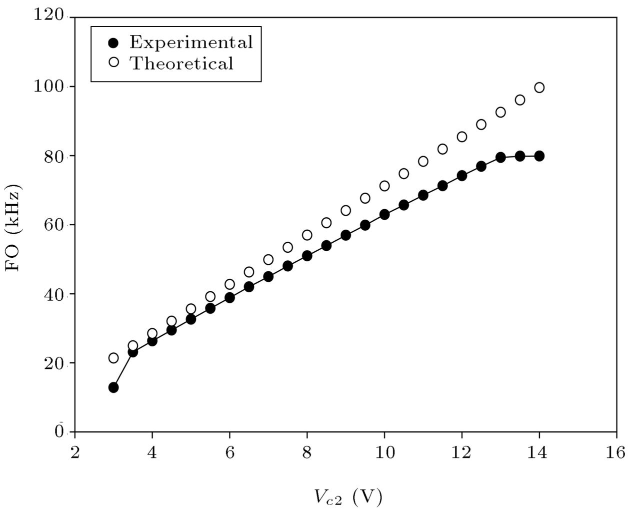


Figure 9. Variations of the frequency of oscillation with control voltage V_{c2}.

CFOAs	Current Feedback Op-Amps;
VCO	Voltage-Controlled Oscillator;
VCR	Voltage-Controlled Resistor.

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Biographies

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Abhirup Lahiri received the BEng degree with the highest honors from the Division of Electronics and Communications, Netaji Subhas Institute of Technology (erstwhile, Delhi Institute of Technology), University of Delhi, India. He has been with STMicroelectronics since 2009, working in different IP groups in the field of analog circuit design. In the past, he was responsible for the development of analog IPs like band-gap references, regulators, crystal oscillators, RC oscillators, LC oscillators, frequency-locked loops, and analog phase-locked loops. His past research works include design of compact analog circuit solutions using novel voltage-mode and current-mode active elements.

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