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Research Paper

Operational Current Amplifiers-Based Quadrature Oscillators Family

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Abstract –

This idea presents a novel family of current-mode quadrature oscillators (CMOS) employing operational current amplifiers (OCAS) as the active building blocks. The proposed oscillator configurations generate two sinusoidal output currents with a precise 90° phase difference, making them highly suitable for quadrature signal generation in communication and instrumentation systems. The circuit topologies are systematically derived to achieve high design flexibility, a low number of active and passive components, and convenient electronic tunability. Analytical derivations for the condition of oscillation (co) and frequency of oscillation (fo) are provided, demonstrating independent control of both parameters through biasing currents or transconductance adjustment. The circuits operate under low supply voltages, making them ideal for modern low-power analog signal processing applications. Simulation results obtained using tanner eda 16.1 with standard CMOS OCA implementations validate the theoretical predictions, confirming low total harmonic distortion, a wide frequency tuning range, and excellent phase accuracy. Experimental results further verify the feasibility and performance of the proposed designs, establishing the presented family as a robust and versatile solution for current-mode quadrature oscillator realization.

Keywords – Current-Mode Quadrature Oscillator, Operational Current Amplifier (OCA), CMOS analog circuits, Quadrature Signal Generation, Low-Power Oscillator Design, Electronic Tunability, Frequency of Oscillation (fo), Condition of Oscillation (co).

1. INTRODUCTION

Analog circuit design is the successful implementation of analog circuits and systems using integrated circuit (IC) technology. Analog circuits and systems have an important role in the implementation and application of very large-scale integration (VLSI) technology. The element of principal importance concerning analog signal processing is the trend of technology. There are mainly four viable integrated technologies for analog Circuits. It is clear that CMOS technology is preferred for digital design. Since analog and digital functions are placed onto a single chip in modern VLSI systems, the use of CMOS technology for analog circuits is also preferred. CMOS process implementation is preferable because CMOS process makes it possible to implement Mixed signal circuit chips with lower cost (Takagi, 2001). During the past years, we have seen a proliferation of mixed analog/digital VLSI ICs realized in state-of-the-art CMOS technologies to optimize cost and power dissipation in consumer products, many of which are pocket size and battery powered (Laker & Sansen, 1994). It has also the advantages of low power consumption and high integration density. Therefore, dominant VLSI technology for analog circuits is CMOS up to GHZ range. Analog processing systems traditionally use input and output voltages which are in charge of carrying the information. The voltage – current duality, which results from the Kirchoff's laws, as well as from the Thevenin's and Norton's theorems, allows analog circuits working from current signals to be obtained, too. Because the measurement of a voltage across an impedance was easier than the measurement of the current flowing through this impedance, engineers used to work with voltages rather than with currents (Fabre, 1995a). Thus, it has become customary in electrical engineering to think of signal processing in terms of voltage variables rather than current variables. This tendency has resulted in voltage signal processing circuits such as voltage amplifiers, voltage integrators, filters which realize a voltage transfer function, etc. In general, amplifiers are classified into four groups as voltage op-amp, current operational amplifier (COA), operational transconductance amplifier (OTA) and operational trans resistance amplifier (OTRA). The voltage op-amp and the OTA have been widely used in several applications for many years, whereas the COA and the OTRA have not gained much attention until recently. The four devices can be arranged into two dual pairs according to adjoint networks. One of the most popular methods for transformation between the current domain and the voltage domain in analog signal processing is the principle of adjoint networks. Using this principle, any voltage mode circuit based on the op-amp can be transformed to a current mode circuit using the COA (Bruun, 1994). The same transformation is possible between the circuits that employ the OTA and the OTRA. The COA is basically a differential current-controlled current source with a very high, ideally infinite, current gain. It exhibits very low, ideally zero, input resistances and very high, ideally infinite, output resistances.

2. THE OPERATIONAL CURRENT AMPLIFIER

An ideal OCA has infinite gain (Ai) and consequently must be used with negative feedback to provide amplification. According to the adjoint networks theorem, an OCA has one input terminal and two differential output terminals given the symbol shown in Figure. Ideally, the OCA has zero impedance at the input port and infinite impedance at the output ports. Its current terminal characteristics adhering to the following relationships.

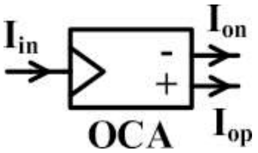


Figure 1. Suggested Symbol for the Oca.

$I_{op} = -Ion = A_i I_{in}$ Where $A_i \to \infty$

A real OCA typically has a large current gain, small input equivalent resistance, and a very large output resistance. The application of negative feedback with sufficient loop gain, forces the input and output impedances to approach their ideal values and hence their effects on the oscillator characteristics can be neglected. The OCA can be incorporated to realize current mode basic amplifiers and functions in a similar manner to their voltage mode counterparts using OpAmps. An OCA in a closed loop with two generalized impedances is shown in Figure. Using this circuit, for example, how to implement a non-inverting amplifier and an inverting integrator which are used in next sections to realize the proposed quadrature oscillator circuit. where s is the complex frequency. The circuit will oscillate if the condition α − β = 0 is satisfied, and the frequency of oscillation will be given by ω = ωo. In the parameters α, β and ωo are functions of the circuit passive components when the oscillators are realized using closed loop amplifiers (e.g. the OpAmp and OCA) whereas they additionally involve the parameters of the active elements when the oscillator circuits

are based on open loop amplifiers, for example, the transconductance of the OTAs. The two fundamental single amplifier based sinusoidal oscillator namely the Wein bridge oscillator and the phase shift oscillator based on the OCA have been developed by the same authors [Unpublished manuscript, under review]. The concept behind quadrature oscillators is the use of an integrator due to its fixed 90◦ phase shift property. The first class of OCA based quadrature sinusoidal oscillators is obtained from their OpAmp based counterpart using the adjoint theorem. There are basically two famous OpAmp quadrature oscillators using two integrator loops topology as shown in Figure. These oscillators use two capacitors and hence are classified as second-order oscillators. The first cir- cuit uses an inverting integrator and a non-inverting integrator whereas the second one employs two inverting integrators and an inverting amplifier.

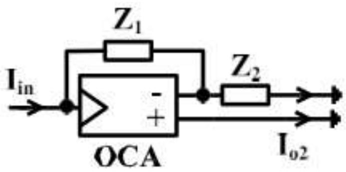


Figure 2. A Generalized Oca Based Circuit

The Barkhausen criterion is commonly used to predict the frequency and condition of oscillation of sinusoidal oscillators. According to this criterion, a second-order oscillator circuit can be described by the characteristic equation given by

$$s^2 + (\alpha - \beta)s + \omega^2 = 0$$

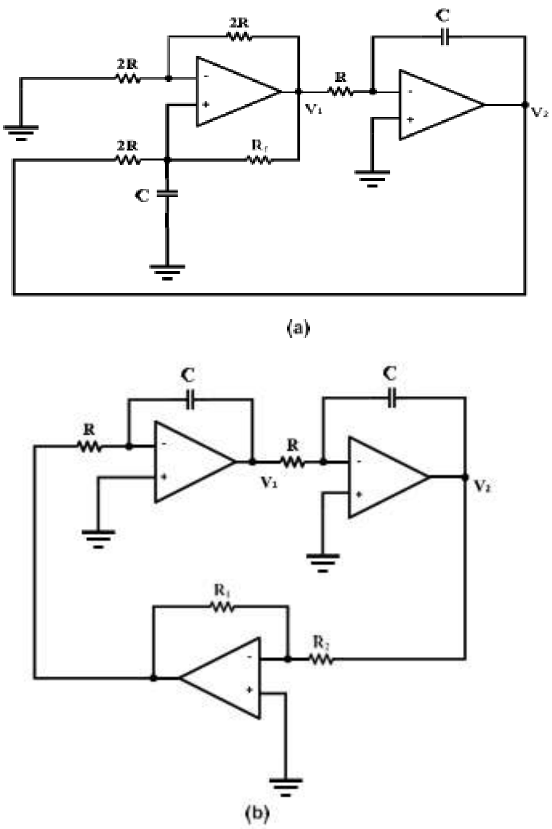
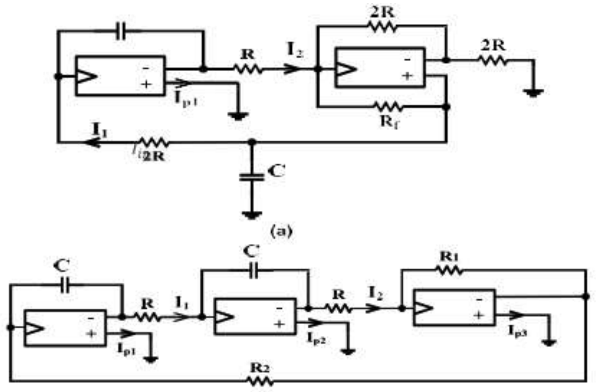


Figure 3. Two Famous Opamp Based Quadrature Oscillators.

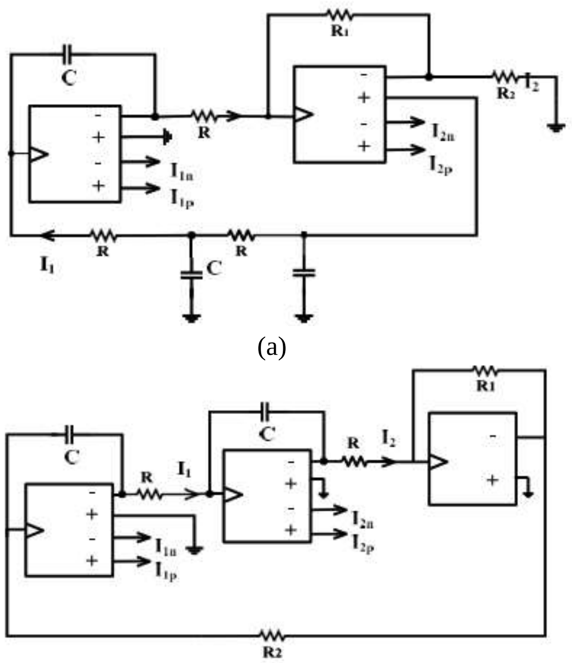
It can be shown that these oscillators provide two voltage quadrature signals whose amplitudes are equal. These are naturally achieved when the signal outputs are taken from both the input and the output nodes of the inverting integrators given that they are OpAmps' outputs. Voltage mode sinusoidal oscillators are fundamental electronics building blocks. But for applications that require current output signals rather than voltage signals, superfluous voltage-to-current converters are mandatory to convert the output signals. On the other hand, applying adjoint network theorem, it can be shown that the corresponding OCA's based oscillator counterparts are shown in Figure. It can be shown that the frequency of oscillation (FO) and the condition of oscillation (CO) of the circuits shown in Figure are identical to their counterparts of Figure. The FO and CO for the circuit in Fig.(a) are given by:



(b)

Figure 4. The Corresponding Oca Based Quadrature Oscillators.

Where Iop1 and Ion1 are the original positive and negative OCA's outputs. Adopting multi-output ocas leads to the circuits shown in Figure.



(b)

FIGURE 5. Extension of the Circuit of Fig. 4 Using Multi-Output Ocas.

These circuits can provide balanced output current signals. But it can be shown that unfortunately the output signals of the circuit in Fig. (a) are not in quadrature. However, it can be seen clearly that the circuit of Fig. (a) can provide only one explicit output current signal Ip1. One the other hand, the circuit of Fig. (b) can provide three output current signals, namely Ip1, Ip2, and Ip3. Obviously, the output current signals are not equal to quadrature signals I1 and I2. Fundamentally, the OCA can at most provide one output current signal since it must be used in negative feedback. Therefore, a multioutput OCA can be developed in order to provide more output signals of which balanced signals are of high interest. The design of a CMOS multi-output OCA will be presented in next section. This means that the output signals are in quadrature and should have equal amplitude at the oscillating frequency. Therefore, this shows that the circuit of Fig. (a) which was originally more efficient in voltage mode would become less efficient in current mode. Alternatively, there are several third-order quadrature oscillators using the OpAmp. In this class, three capacitors and three OpAmps are adopted. Although third order oscillators are not canonic, they have higher accuracy, higher

Quality factor, and lower harmonic distortion than the second-order oscillators. It can be shown in a similar manner that the oscillators can be converted to their OCA based counterparts but their realizations would require at least three OCAs.

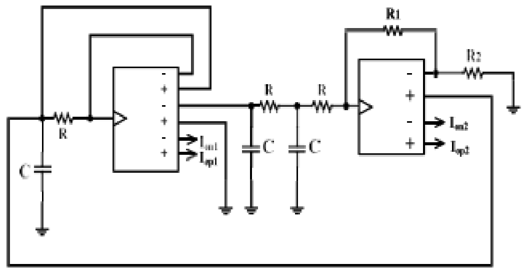


Figure 6. The Proposed Quadrature Oscillator with Only Two Ocas.

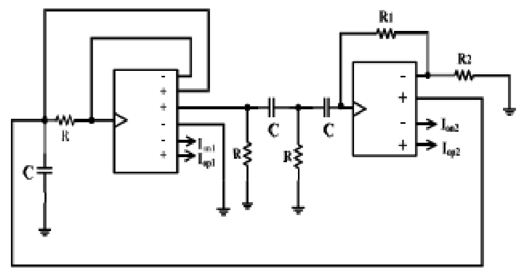


Figure 7. A Second Quadrature Oscillator Using Only Two

Ocas.

In fact, the main source of error is the finite output resistance of the OCA that introduces loss in the integrator's gain. Assuming a resistor Ro in parallel with the integrator capacitor in the oscillator of Figure, non-ideal analysis prevails the following non-ideal FO and CO. In fact, a similar oscillator can be obtained from the circuit of Figure by replacing the inverting integrator and the passive low pass network with a non-inverting integrator and high pass network as shown in Figure. In fact, it can be seen that the oscillator of Figure employs only grounded capacitors and hence it is more attractive for IC applications. Both of these oscillators have FO and CO.

3. RESULTS

The oscillator of Figure was simulated in a standard 150 nm CMOS process using Tanner. The CMOS realization utilized and shown in Figure was adopted. The supply voltage and the biasing currents are set to ±0.9V and 10µA, respectively. The

total power consumption of the OCAs with two stages and three stages are 171µW and 207µW, respectively. In this work, the results obtained from the oscillator of Figure are presented. The quadrature oscillator was designed with R=15k▲ and the capacitors C were varied the oscillation frequency.

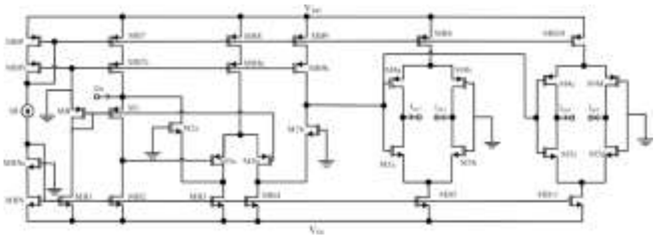
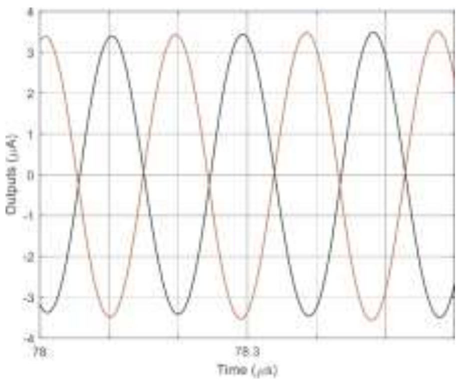


Figure 8. A possible CMOS realization of the multi-output OCA.



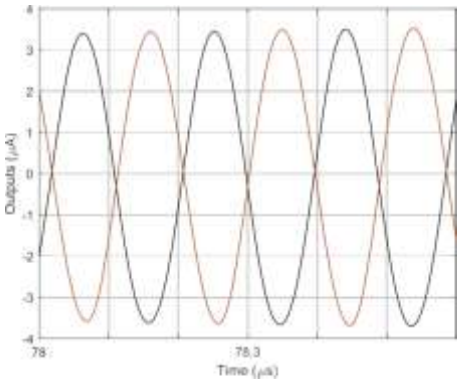


Figure 9. Simulation Results Showing the Differential Signals: Iop1 and Ion1.

The error between the simulation results and the theoretical results was monitored to be within 5%. The resistance of R2 was selected to be 10k▲ while resistor R1 was varied until oscillation started. It was observed that for oscillation frequencies up to 5.3MHz the error was within the limit. At this point C was 1.9pF which corresponds to an ideal oscillation frequency of 5.6MHz. The relatively small error can be explained by observing that two non-ideal opposing factors affect fo. The error caused by Ro, as described, leads to an increase in fo, while the parasitic capacitances contribute to a decrease in fo. Simulation results of the differential output signals Ion1 &Iop1 and Ion2 &Iop2 are shown in Figures, respectively. It show the quadrature signals Ion1 & Ion2 and Iop1 & Iop2, respectively. Finally, the corresponding Lissajous plots using the signals in figures. The CMOS COA of Fig. 14 was fabricated in a standard 150 nm CMOS process.

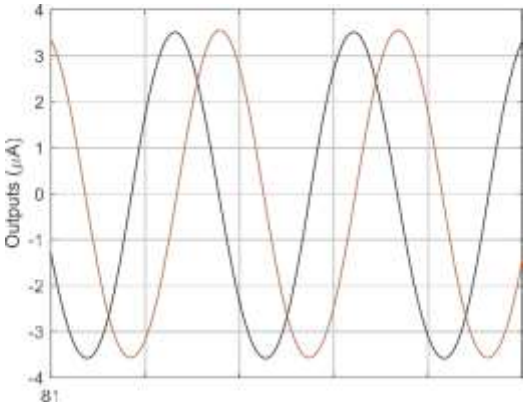


Figure 10. Simulation results showing the differential signals: Ion1 and Ion2.

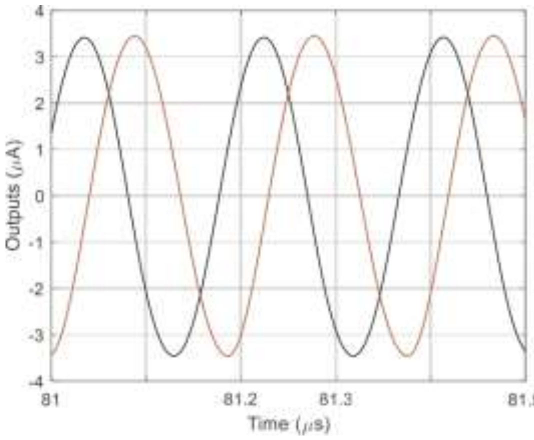
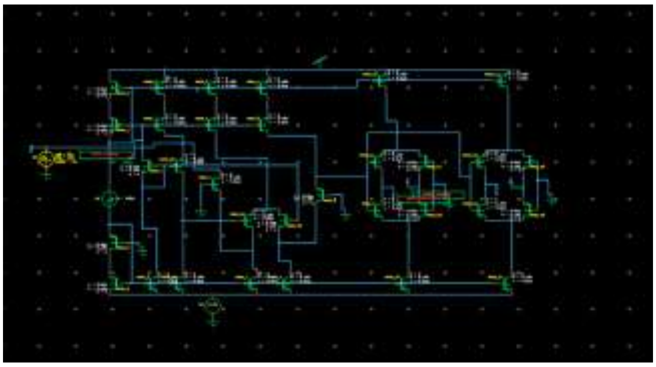
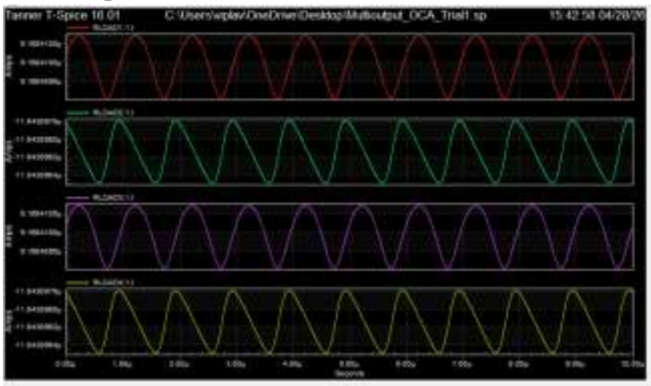


Figure 11. Simulation results showing the differential signals: Iop1 and IoP2.

Oca Schematic Circuit



OCA Output



CONCLUSION

Voltage mode sinusoidal oscillators are fundamental electronics building blocks. But for applications that require current output signals rather than voltage signals, superfluous voltage-to-current converters are mandatory to convert the output signals. This paper has explored the various architectures of quadrature oscillators using the OCA. It shows that following the adjoint network theorem and employing traditional integrators, the oscillators would employ at least 3 OCAs to provide explicit balanced output current signals. Consequently, this work presented a novel integrator that enables the realization of the desired oscillator using only two OCAs. Actually, the proposed oscillator is not only canonic in terms of active amplifier count but also it exhibits the advantages of third-order oscillators. Extensive simulation results as well as experimental results obtained from primary prototype fabricated using standard 150 nm CMOS process are provided. In fact, this work concentrates at this leading stage on pre- sending the mathematical foundation/the systematic approach used to develop this novel oscillator and verifying its workability. Future works may implement a fully integrated version of the proposed oscillator and further investigate its performance characteristics that can continuously be optimized to fulfil desired system-level specifications. As we look to the future, the demand for more efficient, reliable, and compact quadrature oscillators will only intensify, particularly with the growing complexity of wireless communication systems and the Internet of Things (IoT). Therefore, challenges remain in terms of further optimizing the power consumption, frequency operating range, size, and accuracy necessitating ongoing research and innovation.

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