A New Active Inductor and Its Application to Wide Tuning Range LC Oscillator

Mahdi Ebrahimzadeh, Farzan Rezaei, Siavash Rezaei

***Abstract*— This paper presents a new structure to reduce noise in an active inductor. Our structure is based on a local common mode feedback. The proposed active inductor is used for implementation a wide tunable low phase noise LC oscillator. By varying control voltage of active inductor from 0.85 V to 1.6 V, the oscillation frequency changes from 86 MHz to 1.137 GHz. The presented structure improves the value of phase noise in the oscillator based on it about 5.5 dBc/Hz in 1 MHz offset frequency. The proposed oscillator is simulated with TSMC 0.18 μm CMOS technology.**

***Index Terms*—Active Inductor, High Quality Factor, LC Oscillator, Wide Tuning Range, Phase Noise**

I. INTRODUCTION

Indeed, there is a critical need for inductive characteristics in high-speed applications. CMOS spiral inductors have found a broad range of applications in high-speed analog signal processing and data communications. But integrated spiral inductors have a number of limitations due to their layouts. These limitations are low quality factor, low self resonance frequency, small and non tunable inductance and need for very large silicon area [1]. Implementation of inductors with active elements, offers several attractive advantages over their spiral counterparts including large and tunable inductance and low silicon consumption. Unfortunately active inductors have high level of noise due to using a number of transistors. One of the applications of inductive characteristic is LC oscillator. Using the active inductor in LC oscillator increases the phase noise of it. Whereas the most important characteristic in an oscillator is phase noise, this high level of noise restricts use of active inductors in oscillator.

Another limitation of LC oscillators with integrated spiral inductors is their narrow tuning range. In these oscillators, frequency tuning is carried out by a varactor instead of capacitor. Theoretically, the VCO tuning range is determined by the maximum-to-minimum capacitance ratio of the varactor ($C_{var,max}/C_{var,min}$). For a typical capacitance ratio in a standard CMOS process, the tuning range of LC-tank VCOs is approximately limited within 30% making them unattractive for wideband applications [2]-[5]. Several techniques have been proposed to enhance the tuning range of the LC-tank VCOs such as switched capacitors and switched inductors. However a wide frequency tuning range can be achieved in cost of additional circuits with considerable increase in the chip area and complexity of control mechanism [6], [7].

LC oscillators based on active inductors overcome their limitation in tuning range [9]. By utilizing a differential active inductor for the LC-tank, the circuit exhibits a very wide frequency tuning range.

In this paper we present a new active inductor with wide tuning range and low noise performance. It is shown that added local common mode feedback scheme to conventional active inductor, reduces the noise as a common mode signal in its terminal. The proposed oscillator base on new active inductor shows better phase noise performance compared to the conventional oscillators.

This paper is organized as follows. Section II discusses about basic floating gyrator– C. Section III introduces proposed active inductor and LC oscillator based on it. Section IV presents the simulation results followed by the conclusion in section V.

II. GYRATOR- C ACTIVE INDUCTOR STRUCTURE

A gyrator consists of two back-to-back connected transconductors. When, one port of the gyrator is connected to a capacitor, as shown in Fig. 1 the network is called the gyrator-C network. If we consider the gyrator– C network shown in Fig. 1, the impedance looking from its input port is given by:

$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{V_{in}^{+} - V_{in}^{-}}{I_{in}} \Rightarrow Z_{in} = \frac{CS}{G_{m1} \cdot G_{m2}} \qquad (1)$$

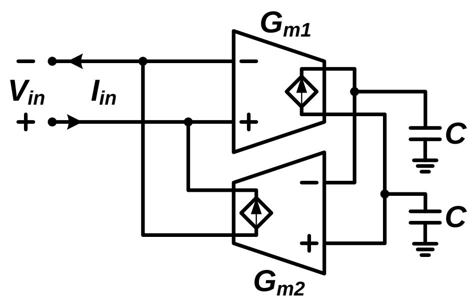


Fig. 1. Floating Gyrator– C Active Inductor Structure.

Equation (1) shows that the gyrator – C network behaves as a floating lossless inductor where its inductance is [10]:

Manuscript Received September 11, 2011.

Mahdi Ebrahimzadeh, Department of Electrical Engineering, Electronics Research Center, Iran University of Science and Technology, Tehran, Iran, Phone No:+98-2188255894/ Mobile No:+98-9133587238, (e-mail: mahdi.ebrahimzadeh@gamil.com).

Farzan Rezaei, Department of Electrical Engineering, Electronics Research Center, Iran University of Science and Technology, Tehran, Iran, Phone No:+98-2188255894, Mobile No: +98-9183656145, (e-mail: rezaei_farzan@iust.ac.ir).

Siavash Rezaei, Department of Computer Engineering, Sharif University of Technology, Tehran, Iran, Phone No:+98-2188255894, (e-mail: srezaei@ce.sharif.edu).

$$L = \frac{C}{(G_{m1}G_{m2})} \tag{2}$$

By considering (2), the inductance of gyrator – C active inductor is directly proportional to the load capacitance C and inversely proportional to the product of the transconductances of the transconductors of the gyrator. When either the input or the output impedances of the transconductors of gyrator – C networks are finite, the synthesized inductors are no longer lossless [8]. Also, the gyrator-C networks are inductive only in a specific frequency range.

III. PROPOSED ACTIVE INDUCTOR

The proposed active inductor is shown in Fig. 2, which is based on gyrator– C structure. M1, M2 transistors are two Gm cells connected back to back. M3, M4 are in common mode configuration and act as voltage buffers. M5, M6 are current source transistors and control the transconductance of M1, M2, so control the inductance of active inductor. Parasitic capacitances of M1-M6 in nodes "a" and "b" have the role of C in gyrator– C structure. For reducing the variations of common mode signal in terminal of inductor, we employ M9-M12.

Reducing the variations of common mode signal in terminals of active inductor results in lower phase noise in oscillator based on it. This is the result of that noise is a common mode signal and our proposed structure reduces common mode variations.

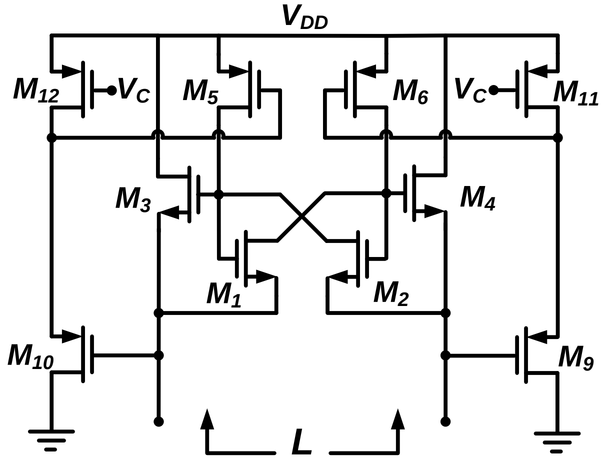


Fig. 2. Proposed active inductor

When the magnitude of common mode signal in terminal nodes of active inductor increases (due to the noise or other interference signals), the source nodes of common drain configured transistors M9 and M10 increases too. So the gate voltage of M5, M6 goes high which leads to lower magnitude of common mode signal in "a" and "b" and therefore terminal nodes. Inductance control is carried out through V_C signal at the gate of M11, M12. Increasing V_C leads to lower voltage in gates of M5, M6 and so increases their currents. So the transconductance of M1 and M2 increases which results in lower Inductance and therefore in an oscillator leads to a higher oscillation frequency.

The proposed tunable active inductor can be applied to realizing narrowband tunable active filters and inductance controlled oscillators. Compared with the varactor diode capacitor, the tunable active inductor has a wider frequency tuning capability because it has a wide tuning range of resistance as well as inductance. Also, it can be easily integrated with other MMIC circuits because it consists of conventional MMIC components.

As shown in Fig. 3, a tunable active inductor is implemented in the resonator of oscillator as a frequency selective element. Compared to the conventional varator controlled oscillator where the oscillation frequency is tuned by the varactor capacitance, oscillation frequency is controlled by the inductance in the presented structure. Also, it is clear that transistors M1 and M2 and capacitor provides a negative resistance.

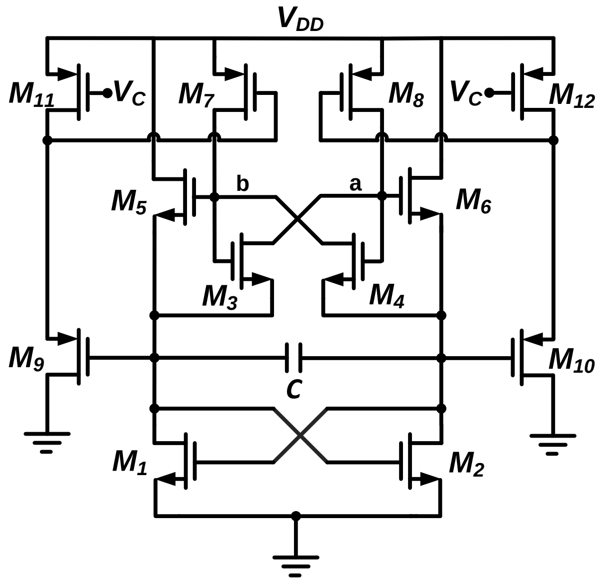


Fig. 3. LC oscillator based on the proposed active inductor

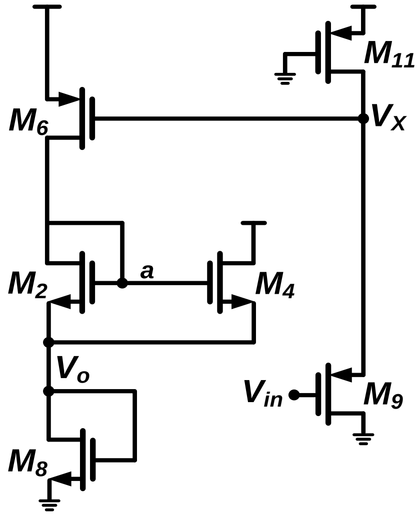
Common mode small signal equivalent circuit of oscillator is depicted in Fig. 4a. In Fig. 4a the feedback loop is opened to compute its common mode gain. Analysis of Fig. 4-b gives the common mode gain as:

$$A_C = -\frac{\dfrac{g_{m6}g_{m9}}{g_{ds11}+g_{m9}}}{g_{ds6}+(g_{m2}+g_{ds6})(g_{m8}/(g_{m2}+g_{m4}))} \tag{3}$$

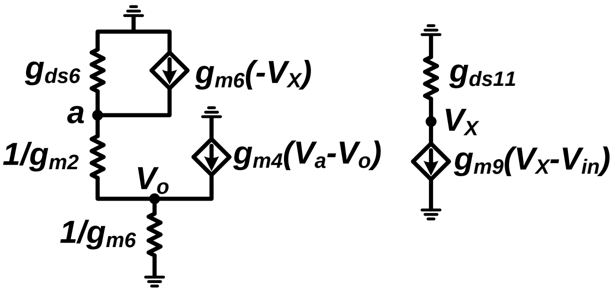
Where g_m is small-signal transconductance of transistors and g_{ds} is their drain-source conductance.

Thus the magnitude of noise in output nodes divided by this gain is:

$$v_{n,new}^2 = \frac{v_{n,con}^2}{(A_V)^2} \tag{4}$$



(a)



(b)

Fig. 4. (a) Opened common mode feedback loop. (b) Small signal equivalent circuit.

IV. SIMULATION RESULTS

At first, we approximate the inductance of the active inductor with L=Im(Z_{in})/ω. Based on this equation, the value of active inductor's inductance is calculated and depicted in Fig. 5. As can be seen, the design has an inductive characteristic in frequency band of DC to 6.9 GHz. For frequencies higher than 6.9 GHz, the imaginary part of the impedance has a negative value and the design has capacitive characteristic. The oscillator based on proposed active inductor is simulated with TSMC 0.18 µm CMOS technology by using ADS software. Tuning range of the oscillator versus control voltage is shown in Fig. 6. It can be observed that there is a wide tuning range, 171 %, from 86 MHz to 1.137 GHz which obtained by varying control voltage from 0.85 V to 1.6 V.

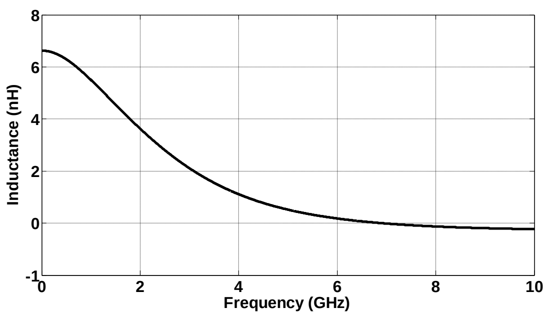


Fig. 5. Simulated inductance of the active inductor

j

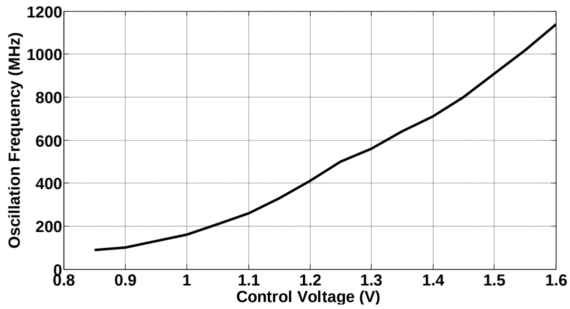


Fig. 6. Oscillation frequency versus control voltage

The simulated output phase noise using the harmonic balance in ADS is plotted as a function of the frequency offset away from the fundamental frequency as shown in Fig. 7. The phase noise of the oscillator is plotted in 100 MHz oscillation frequency. It exhibits -102 dBc/Hz phase noise at 1 MHz offset frequency.

The phase noise of the oscillator can be decreased by increasing the resonating capacitance (i.e. adding extrinsic capacitance), which must be accompanied by a reduction in the simulated inductance value to maintain the same oscillation frequency. The latter can only be achieved by increasing the bias current (g_m of the differential pairs), thus increasing the power consumption of the overall circuit. Alternatively, the active inductor based oscillator can achieve the same phase noise performance with a reduction in power consumption by employing the crystal-like LC-tank structure proposed in [11]. Generally, the phase noise of an actively tuned oscillator can be reduced at the expense of increased chip area.

Comparison results of proposed oscillator with other similar works are summarized in Table I.

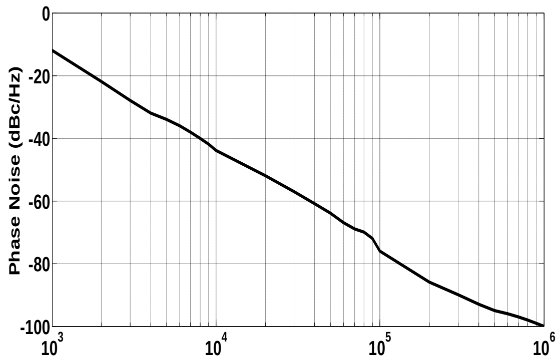


Fig. 7. Oscillator phase noise in 100 MHz oscillation frequency

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

Table I. Main specifications of proposed oscillator compared with similar works

	[12]	[13]	[14]	[15]	This work
Technology	0.35 µm CMOS	1 µm FET	0.8 µm CMOS	0.2 µm CMOS	0.18 µm CMOS
Supply Voltage (V)	3	9	3	1.8	1.8
Tuning Range	100 MHz - 900MHz	1.73 GHz – 2.07 GHz	450MHz - 1.16GHz	NA	86 MHz – 1.137 GHz
Phase Noise (dBc/Hz)	-102 at 1 MHz Offset Frequency	-100 at 1 MHz Offset Frequency	-92 at 1 MHz Offset Frequency	-81 at 500 kHz Offset Frequency	-102 at 1 MHz Offset Frequency

V. CONCLUSION

In this paper, a new active inductor is presented to reduce noise in gyrator– C structure. In the proposed structure, using a common mode feedback technique, noise as a common mode signal is decreased. So the phase noise in an oscillator based on it, is reduced about 5.5 dBc/Hz. Proposed oscillator is tunable from 86 MHz to 1.137 GHz for 0.75 V variation in control signal. The circuit is simulated with TSMC 0.18µm CMOS technology by using ADS software.

ACKNOWLEDGMENT

The authors would like to thank from Iran Telecommunication Research Center for financial and technical support.

REFERENCES

1. A. M. Niknejad, R. G. Meyer, "Analysis, design, and optimization of spiral inductors and transformers for Si RF ICs," *IEEE Journal of Solid State Circuits*, vol. 33, no. 10, pp. 1470-1481, Oct. 1998.
2. Byunghun Min, Hanggeun Jeong, "5-GHz CMOS LC VCOs With Wide Tuning Ranges," *IEEE Microwave and Wireless Components Letters*, vol. 15, no. 5, pp. 336-338, May 2005.
3. C.-M. Hung, N. Barton, "Low phase noise wide tuning range digitally-controlled LC oscillator using switchable inductor," *Electronics Letters*, vol. 45, no. 17, pp. 890-892, Aug. 2009.
4. Tomar, A., Pokharel, R., Kanaya, H., Yoshida, K, "Design of digitally controlled LC oscillator with wide tuning range in 0.18um TSMC CMOS technology," *Microwave Conference*, 2008. *APMC* 2008. *Asia-Pacific*, pp. 1-4, Dec. 2008.
5. Wenhua Tan, Guican Chen, Hong Zhang, "A 1-GHz LC Voltage-Controlled Oscillatorwith High Linearity and Wide Range," *Electron Devices and Solid-State Circuits*, 2008. *EDSSC* 2008. *IEEE International Conference on*, pp. 1-4, Dec. 2008.
6. Kao, H.L., Yang, D.Y., Chang, Y.C., Lin, B.S., Kao, C.H., "Switched resonators using adjustable inductors in 2.4/5 GHz dual-band LC VCO," *Electronics Letters*, vol. 44, no. 4, pp. 299-300, Feb. 208.
7. Axel D. Berny, Ali M. Niknejad, Robert G. Meyer, "A 1.8-GHz LC VCO With 1.3-GHz Tuning Range and Digital Amplitude Calibration," *IEEE Journal of Solid State Circuits*, vol. 40, no. 4, pp. 909-917, Apr. 2005.
8. Liang-Hung Lu, Hsieh-Hung Hsieh,Yu-Te Liao, "A Wide Tuning-Range CMOS VCO With a Differential Tunable Active Inductor," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 9, pp. 3462-3468, Sep. 2006.
9. M.M. Reja, I.M. Filanovsky, K. Moez, "Wide tunable CMOS active inductor," *Electronics Letters*, vol. 44, no. 25, p. 1461–1463, Dec. 2008.
10. F. Yuan, *CMOS Active Inductors and Transformers Principle, Implementation, and Applications*. New York, USA: Springer, 2008.
11. Craninckx, J. Steyaert, M., “Low-Noise Voltage-Controlled Oscillators Using Enhanced LC-Tanks” *IEEE Transactions on Circuits and Systems II, Analog and Digital Signal Processing*, vol 42, no 12, pp 794 - 804, December 1995.
12. Y. Wu, M. Ismail, H. Olsson, "CMOS VHF/RF CCO based on active inductors," *Electronics Letters*, vol. 37, no. 8, pp. 472-473, Apr. 2001.
13. Yong-Ho Cho; Song-Cheol Hong; Young-Se Kwon, "A novel active inductor and its application to inductance-controlled oscillator," *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, no. 8, pp. 1208-1213, Aug. 1997.
14. Thanachayanont, A., Payne, A, "CMOS floating active inductor and its applications to bandpass filter and oscillator designs," *Circuits, Devices and Systems, IEE Proceedings*, vol. 147, pp. 42-48, Feb. 2000.
15. Haiqiao Xiao, Schaumann, R, "A low-voltage low-power CMOS 5-GHz oscillator based on active inductors," *Electronics, Circuits and Systems, 2002. 9th International Conference on*, vol. 1, pp. 231-234, Sep. 2002.

AUTHORS PROFILE

Mahdi Ebrahimzadeh (IEEE Student Member’08) was born in Ardakan, Iran, in 1985. He received the B.S. degree in electronics engineering from Isfahan University of Technology in 2007 and the M.S. degree in electrical engineering from Iran University of Science and Technology, Tehran, in 2010, where he is currently engaged in research toward the Ph.D. degree in electrical engineering.
His present research interests include RF integrated circuits with an emphasis on active inductors and filters, oscillators, frequency synthesizers and high frequency data converters. During 2008-2010 he was with the Electronics Research Center in Iran University of Science and Technology.

Farzan Rezaei was born in Khomein, Iran. He received B.Sc. and M.Sc. degree in electronic engineering from Shahid Beheshti University (SBU) and Iran University of Science and Technology (IUST) Tehran, Iran in 2007 and 2009 respectively. He is currently working toward the Ph.D. degree at the Iran University of Science and Technology from 2010. His research interest is in integrated CMOS low voltage low power analog and RF circuits.

Siavash Rezaei was born in Khomein, Iran. He received B.Sc. degree in computer engineering from Shahid Beheshti University (SBU) Tehran, Iran in 2010. He is currently working toward the M.Sc. degree at the Sharif University of Technology from 2010. His research interest is in fault-tolerant integrated CMOS analog and digital circuits.