Electronically Tunable Current-Mode Square-Root-Domain First Order All-Pass Filters and Their Quadrature Oscillator Applications

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***Abstract*—This paper proposes square-root-domain current-mode first order inverting and non-inverting all-pass filters. The proposed filters are designed by using state-space-synthesis method with current-mode square-root circuits, squarer/divider circuits, current mirrors, current sources and grounded capacitors without any external resistors. Therefore, the proposed filters are appropriate to develop into an integrated circuit. The center frequency can be adjusted electronically by changing the values of the external current sources. A current-mode quadrature oscillator has been included to be an example for the practice. The proposed oscillator is obtained by cascading inverting and non-inverting all-pass filters loop. 3 Volts power supply was used to operate the all-pass filter circuits and the oscillator circuit. In order to demonstrate the performances of them, the PSPICE simulations have been provided to confirm the theoretical analyses. The filters are simulated by using TSMC 0.25 µm Level 3 CMOS process parameters for this purpose.**

***Index Terms*—all-pass filters, current mode circuits, quadrature oscillator, square-root-domain**

I. Introduction

The important subclasses of companding filters and dynamic translinear circuits consist of square-root-domain filters [1]-[6]. Companding circuits are beneficial and can be used in lower voltage and power values, in large dynamic ranges and in high frequency practices and also in bias currents that are tunable in an electronic tunable manner [1]-[6]. In companding filters, input signals are first compressed after which they are processed in a suitable manner and finally they are expanded at the outlet. The operating principle of companding filters is based on the exponential I-V characteristic of BJT and the MOSFETs at the weak inversion region. The quadratic law of MOSFET was suggested in 1987 by Bult [7]. MOS translinear (MTL) feature was derived by Seevinck [8] based on the bipolar translinear (BTL) principle of Gilbert [9]. The quadratic law of MOSFET at the linear and saturation region has been used in [10]-[12]. Square-root-domain filters use MOSFETs operated in saturation region. The quadratic relationship between drain current and gate-source voltage of MOSFETs constitute the bases of these filters [10]. Square-root-domain filters have been designed by using different synthesis method [2], [10], [13]. In the year 1996, the state-space-synthesis methodology was suggested to be used in the design of square-root-domain filters [14].

Up to now, a number of square-root-domain first order all-pass filters have been presented by the authors in the literature. The first order current-mode square-root-domain all-pass filter that is formed by using the N-cell and P-cells is given in [15]. Square-root-domain voltage-mode first order all-pass structure designed by using state-space-synthesis method is presented in [16]. The bad aspect of this proposed circuit is that the circuit is designed in voltage-mode. Square-root-domain current-mode first order inverting all-pass filter is given in [17]. First order all-pass filter which is derived using transfer function decomposition procedure and state-space-synthesis method is proposed in [18].

Many analog signal processing devices consist of parts such as all-pass filters which are among the most important components. “Phase Shifters” is another name given to them. The reason for this is their producing delay which is dependent on the frequency they also keep the input signal amplitude at a constant level over the range of frequency [19]. In this paper, square-root-domain current-mode first order inverting and non-inverting all-pass filters are proposed.

An oscillator is an important fundamental building block, which is commonly used in electrical-electronics engineering applications. Between a few oscillator types, quadrature oscillator is widely used. The reason for the use of quadrature oscillator is that it ensures that there are 2 sinusoids which have a phase difference of 90°. The areas in which the quadrature oscillator is used in telecommunication are as follows:

- Single sideband generators

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- Quadrature mixers
- Vector generators (in measurements)

This is the reason why they are considered as significant elements in various communication systems. [20]-[22]. In the literature, there are proposed various applications of quadrature oscillator circuits using active devices building block. An electronically tunable current-mode quadrature oscillator derived from first order all-pass filter is proposed in [23]. A MOS-C third order quadrature oscillator using OTRA is presented in [24]. Unfortunately, many proposed circuits have some weaknesses. In some of these applications, oscillation condition and oscillation frequency cannot be electronically adjusted [25] and [26]. The proposed circuit in [27] use floating capacitor, the circuits which use floating capacitor are not suitable to be manufactured in the future. There is use of external resistors [26]-[28].

As an application, a current-mode quadrature oscillator employing the proposed all-pass filters is also presented. The proposed filter circuits and oscillator circuit suggested in this study have various advantages over the other filters and oscillator circuits such as the fact that they are current-mode, that they need only transistors and grounded capacitors without any external resistors, that they provide a large dynamic range and low THD, that the center frequency can be adjusted electronically via external current sources, that they are suitable for low voltage/power applications, low fabrication cost, and operating with a power supply of 3 Volts. The performance of the proposed circuits is verified using PSPICE simulations.

II. The Proposed Square-Root-Domain Current-Mode First Order All-Pass Filters

In this paper, square-root-domain current-mode first order inverting and non-inverting all-pass filters are designed by using the state-space-synthesis method. First order all-pass filter's general transfer function is given in (1), where ω_0 is the center frequency and a_1 is the gain of the filter.

$$H(s)=\frac{Y(s)}{U(s)}=-a_1\frac{s-\omega_0}{s+\omega_0} \tag{1}$$

The transfer function of first order inverting all-pass filter is expressed as:

$$H^-(s)=\frac{Y(s)}{U(s)}=\frac{-s+\omega_0}{s+\omega_0} \tag{2}$$

The transfer function of first order non-inverting all-pass filter is expressed as:

$$H^+(s)=\frac{Y(s)}{U(s)}=\frac{s-\omega_0}{s+\omega_0} \tag{3}$$

Transfer functions were transformed to the following state-space equation [29]:

For inverting and non-inverting all-pass filters:

$$\dot{x}_1=-\omega_0 x_1+2\omega_0 u \tag{4}$$

The output equations are [30]:

For inverting all-pass filter:

$$y^-=x_1-u \tag{5}$$

For non-inverting all-pass filter:

$$y^+=-x_1+u \tag{6}$$

In places where the input is shown as u, the output is shown as y, and the state variable is shown as x_1. Equation (4) can be converted into a set of nodal equations if square mappings on the input and the state variables are used. For this reason, the mappings given below may be applied to the quantities in the equation:

$$x_1=\frac{\beta}{2}(V_1-V_{th})^2 \tag{7}$$

In places where $\beta=\frac{\mu_0 C_{ox}\omega}{L}$ stands for transconductance, V_1 represents gate-source voltage and V_{th} represents the threshold voltage. If we take the derivative of the saturation equation, we get:

$$\dot{x}_1=\beta\dot{V}_1(V_1-V_{th}) \tag{8}$$

The relationship given above has been applied to (4). After this application, the nodal equation given below has been formed.

For inverting and non-inverting all-pass filters:

$$C\dot{V}_1=-\frac{\omega_0 C}{\sqrt{2\beta}}\sqrt{x_1}+2\frac{\omega_0 C}{\sqrt{2\beta}}\frac{u}{\sqrt{x_1}} \tag{9}$$

In this equation, C is a capacitor value resembling a multifunction factor. $C\dot{V}_1$ in (9) can be accepted as time dependent current that is grounded via a capacitor.

I_0 is a positive constant which is given by:

$$I_0=\frac{\omega_0{}^2C^2}{\beta} \tag{10}$$

Equation (9) can be arranged as follow:

For inverting and non-inverting all-pass filters:

$$C\dot{V}_1=-\sqrt{\frac{I_0x_1}{2}}+2\sqrt{\frac{I_0u^2}{2x_1}} \tag{11}$$

The output equations are:

For inverting all-pass filter:

$$y^-=x_1-u=\frac{\beta}{2}(V_1-V_{th})^2-u \tag{12}$$

For non-inverting all-pass filter:

$$y^+=-x_1+u=-\frac{\beta}{2}(V_1-V_{th})^2+u \tag{13}$$

It is necessary to connect the filter structures to two sub-circuits in order to provide the suggested filter circuit. The structures of the sub-circuits are given below, respectively: Sub-circuit 1: A square-root-domain structure; Sub-circuit 2: A square-root-domain structure and squarer/divider structures [10]. The MOS translinear MTL circuits consist of current-mode square-root and current-mode squarer/divider circuits [30]-[32]. In Fig. 1 and Fig. 2, the square-root and squarer/divider circuits are demonstrated [30]-[32]. Fig. 3 demonstrates the block diagram of the second sub-circuit. Reference [31] provides the current-mode squarer/divider circuit.

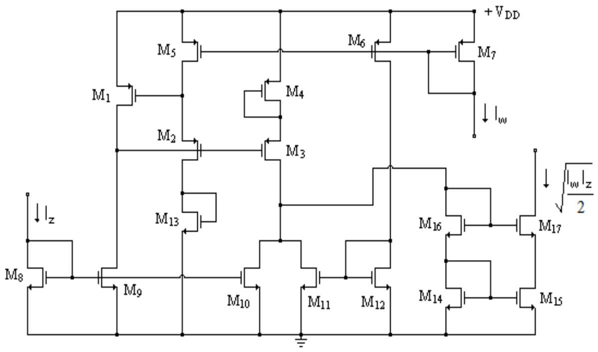

Figure 1. Current-mode square-root-domain circuit.

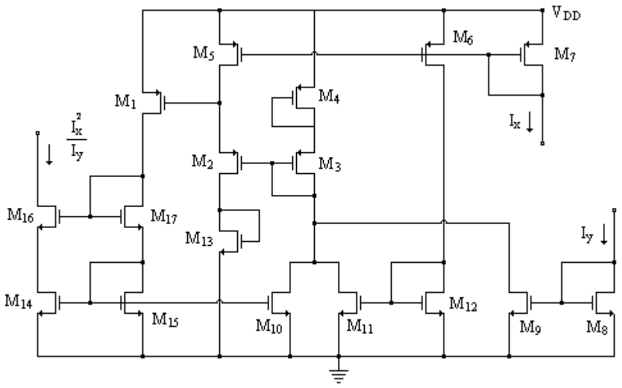

Figure 2. Current-mode squarer/divider circuit.

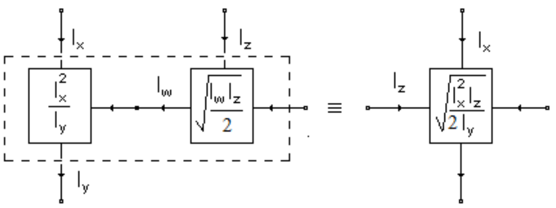

Figure 3. Sub-circuit 2: Current–mode square–root circuit connected to squarer/divider circuit Current-mode square-root circuit.

Fig. 4 demonstrates the realizations of the first order square-root-domain inverting all-pass filter circuit. This circuit has been obtained by using (11) and (12), and with square-root and squarer/divider sub-circuits [17]. Fig. 5 demonstrates the first order square-root-domain non-inverting all-pass filter circuit. The circuit has been obtained by using (11) and (13), and with square-root and squarer/divider sub-circuits. Equation (14) demonstrates the all-pass filters' center frequency. It may be adjusted by changing I_0.

$$\omega_0 = \frac{\sqrt{I_0 \beta}}{C} \tag{14}$$

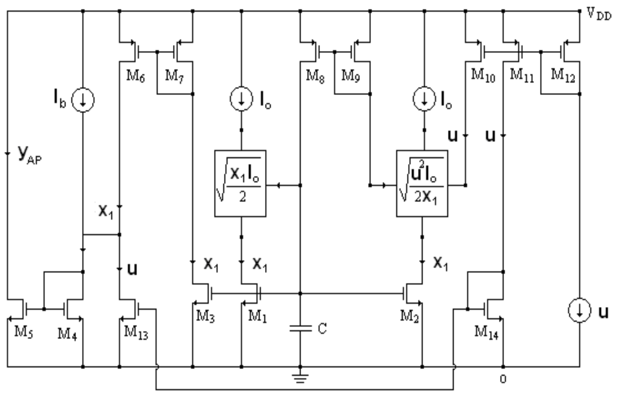

Figure 4. Square-root-domain current-mode first order inverting all-pass filter circuit.

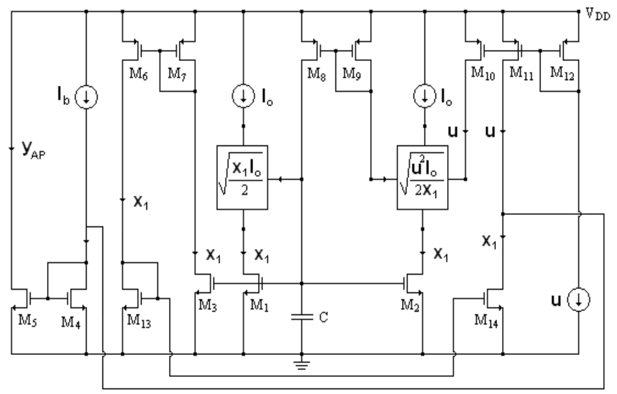

Figure 5. Square-root-domain current-mode first order non-inverting all-pass filter circuit.

A. Simulation Results of First Order All-Pass Filters.

A square-root circuit and a square-root circuit constitute the suggested square-root-domain current-mode first order inverting and non-inverting all-pass filters; and they are connected to squarer/divider circuit; current sources; current mirrors; and also to a grounded capacitor. The designed circuits were simulated by TSMC 0.25 µm Level 3 CMOS model parameters in PSPICE simulation program. The circuit parameters for inverting all-pass filter are given as follows; the supply voltage of the filter circuit has been selected as V_{DD} = 3 V, the value of the capacitor has been selected as C = 10 pF, and the values of the DC current sources have been selected as I_0 = 135 µA, I_b = 184 µA. The circuit parameters for non-inverting all-pass filter are given as follows; the supply voltage of the filter circuit has been selected as V_{DD} = 3 V, the value of the capacitor has been selected as C = 10 pF, and the values of the DC current sources have been selected as I_0 = 135 µA, I_b = 53 µA. Dimensions of MOS transistors for proposed inverting and non-inverting all-pass filter circuits are given in Table I.

The all-pass filter circuit's center frequency under these circumstances is f_0 = 1.995 MHz. The gain and phase responses of the all-pass filters along with the theoretical results have been given in Fig. 6, Fig. 7, Fig. 8, and Fig. 9 with ideal responses, respectively.

TABLE I. DIMENSIONS OF MOS TRANSISTORS

Circuit	Transistor	ω (μm)	L (μm)
Square-root circuit	M_2-M_9, M_{12}, M_{14}-M_{17}	14	0,7
	M_1, M_{10}, M_{13}	7	0,7
	M_{11}	3,5	0,7
Squarer/divider circuit	M_1, M_2, M_{10}, M_{11}, M_{13}	7	0,7
	M_3-M_9, M_{12}, M_{14}-M_{17}	14	0,7
All-pass filter circuits	M_1, M_2, M_3	5	5
	M_4-M_7, M_9-M_{14}	30	0,5
	M_8	60	0,5

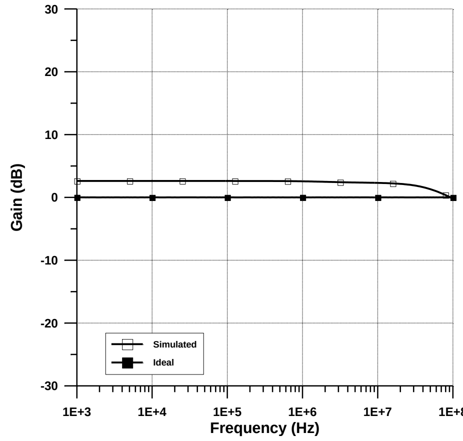

Figure 6. Inverting all-pass filter's gain response.

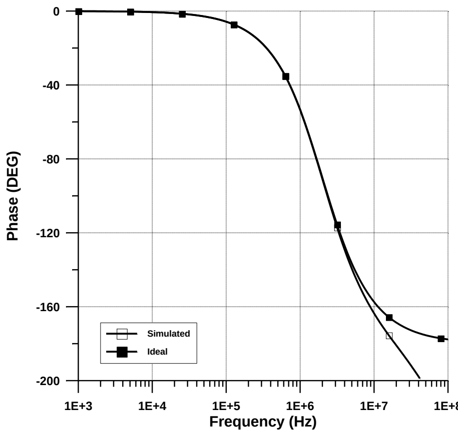

Figure 7. Inverting all-pass filter's phase response.

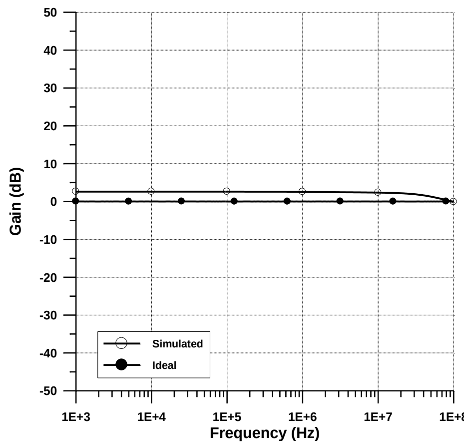

Figure 8. Non-inverting all-pass filter's gain response.

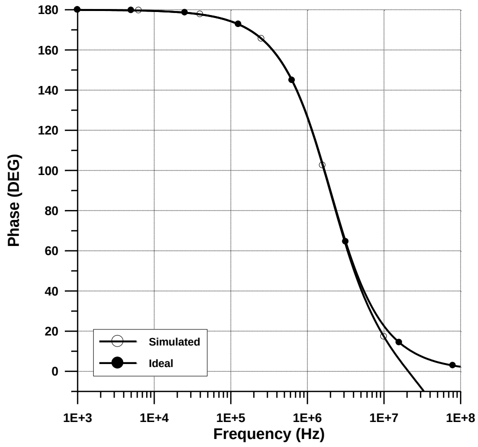

Figure 9. Non-inverting all-pass filter's phase response.

It can be seen from the equations that the center frequency of the filters can be adjusted. Different gain responses have been attained for different center frequency values by changing the values of the DC current sources I_0 in all-pass filter circuits. The gain and phase responses obtained for the different values of the DC current sources I_0 of the filter circuits have been given in Fig. 10, Fig. 11, Fig. 12, and Fig. 13.

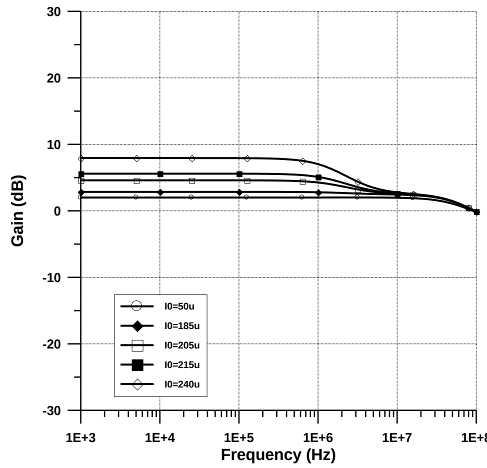

Figure 10. Inverting all-pass filter's electronically tunable gain response.

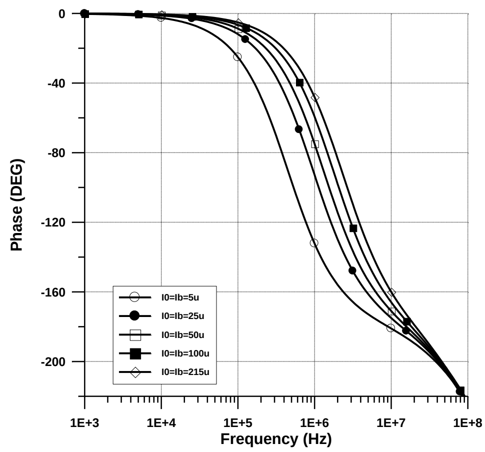

Figure 11. Inverting all-pass filter's electronically tunable phase response.

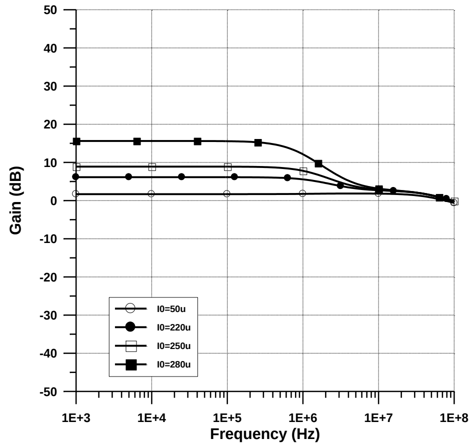

Figure 12. Non-inverting all-pass filter's electronically tunable gain response.

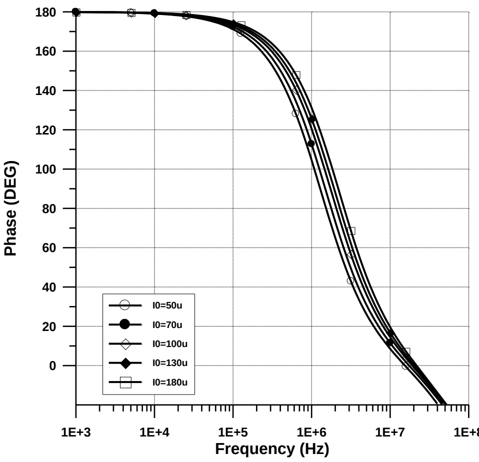

Figure 13. Non-inverting-all-pass filter's electronically tunable phase response.

III. Application Example as Quadrature Oscillator

Fig. 14 demonstrates the application of the suggested all-pass filters. Inverting and non-inverting all-pass filter blocks were combined together to form a quadrature oscillator. The schematic of quadrature oscillator is shown in Fig. 15.

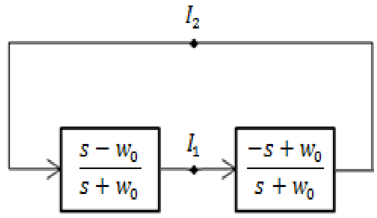

Figure 14. Block diagram for quadrature oscillator.

By using TSMC 0.25 µm CMOS Level 3 model parameters, the quadrature oscillator was simulated in PSPICE simulation program. The circuit parameters for quadrature oscillator are given as follows; the supply voltage of the filter circuit has been selected as V_{DD} = 3 V, the value of the capacitor has been selected as C = 10 pF, and the values of the DC current sources have been selected as I_{0p} = I_{0n} = 75 µA, I_{bp} = 140 µA, I_{bn} = 53 µA. This yields an oscillation frequency of 1.2 MHz.

The sinusoidal signal current outputs are shown in Fig. 16. It can be seen that the outputs have approximately 90 º phase difference. The frequency spectrum of sinusoidal signal output of Fig. 16 is shown in Fig. 17.

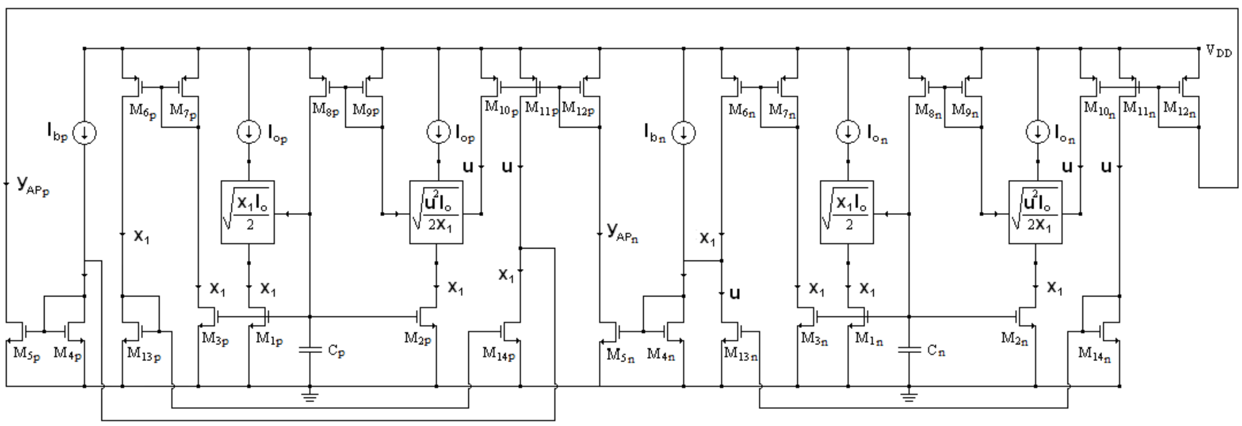

Figure 15. Square-root-domain quadrature oscillator.

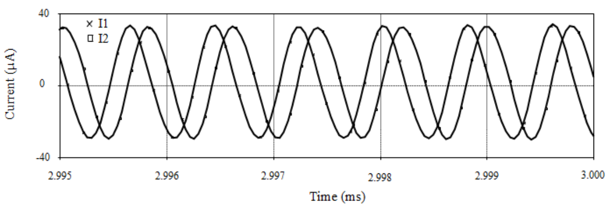

Figure 16. The simulation result of quadrature oscillator circuit.

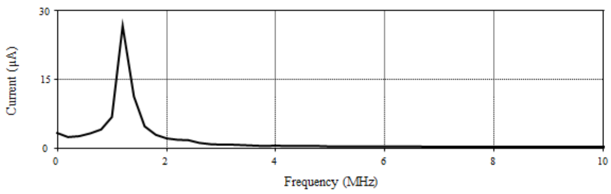

Figure 17. The output spectrum of the oscillator.

IV. CONCLUSION

This study suggests all-pass filters whose characteristics are current-mode, first order square-root-domain inverting and non-inverting. In addition, a systematic synthesis procedure is also provided, and the purpose for this is deriving the filter circuits. State-space-synthesis method was used to generate the filter circuit. Since the filter circuits consist merely of grounded capacitors and MOS transistors, they have simple structures and are suitable for integrated circuit implementations. Being tuned electronically is the most significant characteristics of the circuit; in other words, the value of the DC current sources can be altered in order to adjust the center frequency of the filters, and this is sufficient. Thus, the proposed first order all-pass filters can be used as an electronically controllable phase shifter. As an application, a quadrature oscillator is included. Oscillators can obtain the desired signal in the desired frequency. Thanks to this feature, the performance and results of electronic circuits can control easily. The suggested all-pass filters being applicable are clear in this context. To confirm the theoretical analyses, the PSPICE simulations are also given.

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