Abstract—In this study, a new design technique for high-Q current-mode bandpass filter using non-inverting lossy integrator is presented. The proposed new CMOS bandpass filter is designed by this new method. The most important advantage of the method uses only non-inverting lossy integrator structure for designing bandpass filters. MOSFETs square-law based non-inverting lossy integrator structure is used for realizing CMOS bandpass filter. At the same time, the proposed CMOS bandpass filter is a companding filter, since companding CMOS non-inverting lossy integrators are employed for realizing the filter circuit. The designed filter has a very simple structure, since it uses only MOSFETs and two grounded capacitors. All transistor aspect ratios (W/L)s are of the same value except for three transistors. The center frequency, the quality factor, and gain of the filter can be adjusted electronically. High-order bandpass filters can be designed using this method due to ability to tune all parameters. The bandpass is tunable in the center frequency range from 1Hz to 150MHz, with a Q quality factor that can be tuned from 1 to 100, (DR > 60dB) dynamic range with THD (<2 total harmonic distortion, and operated with a single supply voltage of 2.5V. The proposed filter can be applied for low voltage/power applications because of companding circuit. The designed circuit has been simulated in PSPICE using TSMC 0.35 μm CMOS process parameters.

Keywords—current-mode circuits, CMOS, bandpass filter, companding circuit, non-inverting lossy integrator, electronically tunable.

I. INTRODUCTION

The current-mode filters have been receiving considerable attention due to their potential advantages such as inherently wide bandwidth, higher slew rate, wider dynamic range, simple configuration, high frequency operation, low voltage operation, and low power consumption [1-4]. An important number of elementary mathematical functions can be obtained easier from current signals rather than from voltage. Mathematical operations of adding, subtracting or multiplying signals represented by currents are simpler to perform than when they are represented by voltages. For this reason, integrated current-mode system realizations are closer to the transistor level than the conventional voltage-mode realizations and therefore simpler circuits and systems should result [1-6]. On the other hand the high order filters can be implemented by using two or more filter blocks in cascade. Many techniques have been proposed in the literature to design the bandpass filter.

The block diagram consisting of lossless and lossy integrators and feedback is commonly used to realize filter circuits by designers [7-13]. The novelty of this study is an application of block diagram based on first-order lowpass or only non-inverting lossy integrator block method to realize high-Q, second-order current-mode bandpass responses. The proposed filter has advantages with respect to other filter structures that minimum components are used to realize a filter function. Then, the feedback is applied to the filter through the filter structure, in order to obtain high quality factor values than 1/2. The quality factor of second-order bandpass filter can be increased by using a feedback circuit that is provides a current gain. The input and output signals are currents, and proposed filter can be described completely in terms of current-mode. It has very simple structure, and can give bandpass responses for a single input. For high-Q filter design, the new approach design method can be widely used due to its simple structure and tunable capability. Also, the filter circuit is very simple, can readily be integrated, are suitable for high-frequency applications, and can operate with a power supply as low as 2.5 V.

Up to now, several second-order bandpass filters have been presented in the literature [14-20]. In this study, the proposed filter has advantages with respect to other bandpass filters that only transistors and grounded capacitors are required to realize the filter circuit. It provides large dynamic range and lower total harmonic distortion. It has a high-Q and the center frequency of the filter can be electronically tuned by changing external current. The quality factor, and gain can be adjusted. It is suitable for low voltage/power applications.

In Section II, the new design method is presented. The proposed of the bandpass filter is discussed in Section III. Simulation results are presented in Section IV.

II. THE PROPOSED HIGH-Q CMOS BANDPASS TUNABLE FILTER

The proposed second-order CMOS bandpass filter is realized by a block diagram. The block-diagram realization can be obtained by combining the non-inverting lossy integrator blocks, k gain block with the three arithmetic blocks as shown in Fig. 1 [12], [13]. The arithmetic block represents a node where the currents are being summed or
subtracted depending on the direction of current flow at that node [12], [13]. Then, the feedback is applied to the filter through the current amplifier circuit, in order to obtain high quality factor values than 1/2. The quality factor of second order bandpass filter can be increased by using a feedback circuit that provides a current gain [12], [20].

From Fig.2, the KCL, and KVL equations can be written [21], [23]:

\[ I_{DS1} = I_{in} + I_{dc} - I_{CAP} \]  \( (4) \)
\[ I_{DS2} = I_{out} + I_{dc} \]  \( (5) \)
\[ V_{CAP} = V_{GS1} = V_{GS2} \]  \( (6) \)

The capacitor current can be given by

\[ I_{CAP} = CV_{CAP} = CV'_{GS2} \]  \( (7) \)

The output current is the drain current of a M2 transistor and derivative of the output current is

\[ i_{DS2} = \dot{i}_{out} = \beta(V_{GS2} - V_{th})V'_{GS2} \]  \( (8) \)

combining (4) with (8) and we obtain

\[ I_{in} + I_{dc} - I_{DS1} = C \frac{\dot{i}_{out}}{\beta(V_{GS} - V_{th})} \]  \( (9) \)
\[ I_{in} - I_{out} = C \frac{\dot{i}_{out}}{\beta(V_{GS} - V_{th})} \]  \( (10) \)
\[ I_{out} + \frac{\beta(V_{GS} - V_{th})}{C} I_{out} = \frac{\beta(V_{GS} - V_{th})}{C} I_{in} \]  \( (11) \)

When the amplitude of \( I_{in} \) is small with respect to \( I_{dc} \), the transconductance \( g_m \) of the output transistor is approximately constant [21]. Therefore, the relation between the capacitor voltage and the output current \( I_{out} \) is almost linear. The transfer function of the filter core can be described by a linear differential equation [21]:

\[ \dot{I}_{out} + \frac{\sqrt{2} \beta I_{dc}}{C} I_{out} = \frac{\sqrt{2} \beta I_{dc}}{C} I_{in} \]  \( (12) \)

Using the Laplace transform, the topology in Fig. 2 is a non-inverting lossy integrator with the following transfer function:

\[ \frac{I_{out}(s)}{I_{in}(s)} = \frac{\omega_0}{s + \omega_0} \]  \( (13) \)

which represents the transfer function of lowpass filter or non-inverting lossy integrator.

The cut-off frequency of the integrator: \( \omega_0 = \frac{\sqrt{2} \beta I_{dc}}{C} \)

The realization of the CMOS bandpass filter circuit using Fig.1 and Fig.2 is shown in Fig. 3.

The proposed filter parameters, \( \omega_0 \), \( A \), \( Q \) were obtained from Fig.1, Fig. 2, and Fig.3 as follows,
The center frequency of filter: \( \omega_c = \sqrt{2 \beta I_{dc}} \).

The gain of filter: \( A \),

The quality factor of filter: \( Q = 1/(2 - k) \)

III. SIMULATION RESULTS

If you are using Word, use either the Microsoft Equation Editor or the MathType add-on (http://www.mathtype.com) for equations in your paper (Insert | Object | Create New | Microsoft Equation or MathType Equation). “Float over text” should not be selected.

The proposed filter was simulated by using TSMC 0.35 \( \mu m \) Level 3 CMOS process parameters. The transistors \( M1-M22, M25 \) aspect ratios are: \( (W/L)_n=(W/L)_p=6\mu m/1\mu m \), and the transistors \( M23, M24 \) and \( M26 \) aspect ratios depend on quality factor and gain. The circuit parameters are chosen as; \( V_{DD}=2.5V \), \( I_{dc}=80\mu A \), \( C=5pF \). The natural frequency of the filter is \( f_0 \approx 10MHz \), Quality Factor of filter is \( Q = 1 \), and gain is \( A = 1 \). The gain response of the bandpass filter is shown in Fig. 4. The phase response of the bandpass is shown in Fig. 5.

The center frequency was observed by changing the external current \( I_{dc} \) as shown in Fig. 6. For this property, the external currents were changed from \( 1\mu A \) to \( 80\mu A \) and the filter center frequency was tuned from 1.2MHz to 10MHz. \( Q \)-tuning characteristics were observed by changing the external current as shown in Fig. 7. For this purpose, \( k \) was changed with varying the values and the \( Q \) was tuned from 1 to 100. The gain \( A \) tuning values can be controlled by changing \( M26 \) aspect ratios.
The output signal’s THD (Total harmonic distortion (%)) was measured with different input current value. The filter was set to 10 MHz center frequency with $I_{dc} = 80 uA$ and the input frequency was also set to the same value. Then, a sinusoidal signal was applied to the filter with different input currents, 0.1uA, 1uA, 5uA, 10uA, 20uA, 40uA and 100uA. The results of total harmonic distortion THD (%) <2. At the same time, the proposed filter provides large dynamic range ($DR > 60 dB$). The performances and properties of the proposed filter are summarized in Table I. The design is based on block diagram and non-inverting lossy integrator. Tolerable differences are observed that realization of this filter in simulation has provided.

### IV. CONCLUSIONS

In this work, a new current-mode CMOS bandpass filter structure is presented. A systematic synthesis procedure to derive the filter circuit is also given. PSPICE simulations are provided to confirm the theoretical analysis. The proposed filter has the following advantages: i) based CMOS and current-mode, ii) has a very simple structure, and employs only MOSFETs and capacitors, iii) provides high-Q bandpass responses simultaneously for a single input signal, iv) suitable for low voltage/power applications, v) can be electronically tuned, vi) has a wide bandwidth, vii) suitable for VLSI (very large-scale integration) technologies.

### REFERENCES


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