A NEW 5TH-ORDER DIFFERENTIAL TYPE CLASS-AB LOG-DOMAIN ELLIPTIC LOWPASS FILTER FOR VIDEO FREQUENCY APPLICATIONS

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ABSTRACT

This paper proposes a new current-mode 5th-order differential type class-AB log-domain elliptic lowpass filter for video frequency applications. The design is based on the state-space synthesis method. The proposed filter has 5.75 MHz cut-off frequency with maximum 0.177 dB passband ripple and attenuation greater than 40 dB at 7.88 MHz. Only BJTs and grounded capacitors were used, and operated with single power supply of 2.5 V. Since the parameters of proposed filter are tunable, it is easy to control of cut-off frequency. This adjustment is accomplished by changing external currents. SPICE simulations are given to confirm the theoretical analysis. For this purpose, the filter is simulated by using both idealized BJT models and AT&T CBIC-U2 type transistors.

I. INTRODUCTION

Without the need for conventional circuit linearization techniques, log-domain filter circuits have a simple and elegant structure, and hold potential to run at high frequencies and operate from low power supplies [1-5]. An important property of log-domain filtering is that it uses companding [2-3], whereby the signals are compressed logarithmically at the input stage before being processed and then expanded exponentially at the output stage. This makes it possible for log-domain circuits to operate with very low supply voltage without sacrificing the dynamic range [5]. Log domain filters are of interest, mainly due to their suitability for low voltage, low power, low impedance levels, large dynamic range, high frequency applications and for being electronically tunable [1-5]. The class-AB circuit structures were applied to design filters by Seevinck to proposed the first Class-AB filter in 1990 [2]. Differential class-AB log-domain filter has low power consumption, low noise, low distortion, high dynamic range, and good linearity comparing to Class A log-domain filter [2-3]. State-space synthesis method is a very powerful and efficient approach for the synthesis of log-domain filters [1]. It provides a very general solution for realizing filter function. The key aspect of the use of state-space methods in this study is that exactly relates internally non-linear filters to equivalent linear systems. Linear state-space models can be used to realize any known externally linear filter [1].

Up to now, several elliptic video filters is reported in the literature [6-8]. To the best knowledge of the authors, proposed filter is the first current-mode differential class-AB log-domain 5th-order elliptic lowpass filter in the literature. At the same time, the literature survey shows that no log-domain elliptic video filters exist. In this study, a new current-mode 5th-order differential type class-AB log-domain elliptic lowpass filter is designed for video frequency range. The proposed filter has advantages with respect to other filter structures that minimum components are used to realize a filter function and, has differential class-AB structure. Only BJTs and grounded capacitors are required to realize the filter circuit, and operated with single power supply of 2.5 V. The filter parameters can be electronically tuned by changing external currents. It provides large dynamic range and lower THD values due to realizing linear system with inherently nonlinear circuit building blocks, differential type class-AB, and companding properties.

II. THE PROPOSED CURRENT-MODE 5TH-ORDER DIFFERENTIAL TYPE CLASS-AB LOG-DOMAIN ELLIPTIC LOWPASS FILTER

A 5th-order elliptic lowpass filter transfer function can be written as follows,

$$T(s)=\frac{Y(s)}{U(s)}=\frac{I_{out}(s)}{I_{in}(s)}=\frac{a_4\omega_0 s^4+a_2\omega_0^{\ 3}s^2+a_0\omega_0^{\ 5}}{s^5+b_4\omega_0 s^4+b_3\omega_0^{\ 2}s^3+b_2\omega_0^{\ 3}s^2+b_1\omega_0^{\ 4}s+b_0\omega_0^{\ 5}} \quad (1)$$

where ω_0 is the cut off frequency of filter. A systematic synthesis procedure to derive the filter circuit is used. The design is based on the state-space synthesis method.

A state-space formulation consists of a set of first order differential equations. The state variables are equal to simple functions of the exponentials of node voltages. There is a one-to-one correspondence between the mathematical formulation and the circuit realization. The transfer function was transformed to the following first-order differential equations:

$$\dot{x}_1 = \omega_0 x_2 + a_4\omega_0 u \tag{2a}$$

$$\dot{x}_2 = \omega_0 x_3 - a_4 b_4 \omega_0 u \tag{2b}$$

$$\dot{x}_3 = \omega_0 x_4 + (a_4 b_4^2 - a_4 b_3 - a_2)\omega_0 u \tag{2c}$$

$$\dot{x}_4 = \omega_0 x_5 - (a_4 b_4^3 - 2a_4 b_3 b_4 + a_2 b_4 + a_4 b_2)\omega_0 u \tag{2d}$$

$$\begin{aligned}\dot{x}_5 &= -b_4\omega_0 x_5 - b_3\omega_0 x_4 - b_2\omega_0 x_3 - b_1\omega_0 x_2 \\ &- b_0\omega_0 x_1 + (a_4 b_4^4 - 3a_4 b_3 b_4^2 + a_2 b_4^2 \\ &+ 2a_4 b_2 b_4 + a_4 b_3^2 - a_2 b_3 - a_4 b_1 + a_0)\omega_0 u\end{aligned} \tag{2e}$$

The output equation is $y = x_1$ (3)

where u is the input, y is the output and, x_1, x_2, x_3, x_4, and x_5 are the state variables. Coefficients of z_1, z_2, z_3, z_4 and z_5 are equal to the following equations:

$$z_1 = a_4 \tag{4a}$$

$$z_2 = a_4 b_4 \tag{4b}$$

$$z_3 = a_4 b_4^2 - a_4 b_3 + a_2 \tag{4c}$$

$$z_4 = a_4 b_4^3 - 2a_4 b_3 b_4 + a_2 b_4 + a_4 b_2 \tag{4d}$$

$$\begin{aligned}z_5 &= a_4 b_4^4 - 3a_4 b_3 b_4^2 + a_2 b_4^2 + 2a_4 b_2 b_4 \\ &+ a_4 b_3^2 - a_2 b_3 - a_4 b_1 + a_0\end{aligned} \tag{4e}$$

Differential type class-AB filter approach is used. For this purpose, state variables, input and output equations must be separated two equations, which are left and right equations [1],[4]. State variables, input and output equations are

$$\begin{aligned}&x_1 = x_{1L} - x_{1R},\ \ x_2 = x_{2L} - x_{2R},\ \ x_3 = x_{3L} - x_{3R}, \\ &x_4 = x_{4L} - x_{4R},\ \ x_5 = x_{5L} - x_{5R} \\ &u = u_L - u_R,\ \ y = y_L - y_R\end{aligned} \tag{5}$$

The left and right equations must be arranged in suitable form for realizing filter circuit. Convenient form of left and right equations as follows;

The convenient form of left hand side,

$$\dot{x}_{1L} = \omega_0 x_{2L} + \omega_0 z_1 u_L - \frac{\omega_0}{I_{f1}} x_{1L} x_{1R} \tag{6a}$$

$$\dot{x}_{2L} = \omega_0 x_{3L} + \omega_0 z_2 u_R - \frac{\omega_0}{I_{f1}} x_{2L} x_{2R} \tag{6b}$$

$$\dot{x}_{3L} = \omega_0 x_{4L} + \omega_0 z_3 u_L - \frac{\omega_0}{I_{f1}} x_{3L} x_{3R} \tag{6c}$$

$$\dot{x}_{4L} = \omega_0 x_{5L} + \omega_0 z_4 u_R - \frac{\omega_0}{I_{f1}} x_{4L} x_{4R} \tag{6d}$$

$$\begin{aligned}\dot{x}_{5L} &= +\omega_0 b_0 x_{1R} + \omega_0 b_1 x_{2R} + \omega_0 b_2 x_{3R} \\ &+ \omega_0 b_3 x_{4R} - \omega_0 b_4 x_{5L} + \omega_0 z_5 u_L - \frac{\omega_0}{I_{f1}} x_{5L} x_{5R}\end{aligned} \tag{6e}$$

$$y_L = x_{1L} \tag{6f}$$

The convenient form of right hand side,

$$\dot{x}_{1R} = \omega_0 x_{2R} + \omega_0 z_1 u_R - \frac{\omega_0}{I_{f1}} x_{1L} x_{1R} \tag{7a}$$

$$\dot{x}_{2R} = \omega_0 x_{3R} + \omega_0 z_2 u_L - \frac{\omega_0}{I_{f1}} x_{2L} x_{2R} \tag{7b}$$

$$\dot{x}_{3R} = \omega_0 x_{4R} + \omega_0 z_3 u_R - \frac{\omega_0}{I_{f1}} x_{3L} x_{3R} \tag{7c}$$

$$\dot{x}_{4R} = \omega_0 x_{5R} + \omega_0 z_4 u_L - \frac{\omega_0}{I_{f1}} x_{4L} x_{4R} \tag{7d}$$

$$\begin{aligned}\dot{x}_{5R} &= +\omega_0 b_0 x_{1L} + \omega_0 b_1 x_{2L} + \omega_0 b_2 x_{3L} \\ &+ \omega_0 b_3 x_{4L} - \omega_0 b_4 x_{5R} + \omega_0 z_5 u_R - \frac{\omega_0}{I_{f1}} x_{5L} x_{5R}\end{aligned} \tag{7e}$$

$$y_R = x_{1R} \tag{7f}$$

The following mappings can therefore be applied to the quantities in equations (Infinite β condition) [1];

$$\begin{aligned}&x_{1L} = I_s e^{V_{1L}/V_t},\ x_{1R} = I_s e^{V_{1R}/V_t},\ \ x_{2L} = I_s e^{V_{2L}/V_t}, \\ &x_{2R} = I_s e^{V_{2R}/V_t},\ x_{3L} = I_s e^{V_{3L}/V_t},\ x_{3R} = I_s e^{V_{3R}/V_t}, \\ &x_{4L} = I_s e^{V_{4L}/V_t},\ x_{4R} = I_s e^{V_{4R}/V_t}\ \ x_{5L} = I_s e^{V_{5L}/V_t}, \\ &x_{5R} = I_s e^{V_{5R}/V_t},\ \ u_L = I_s e^{V_{0L}/V_t},\ u_R = I_s e^{V_{0R}/V_t}\end{aligned} \tag{8}$$

where I_s is the saturation current, V_t is the thermal voltage, $V_t = kT/q$. The above relationships are applied (6a), (6b), (6c), (6d), (6e), and (6f) in order to realized left side. Scaling factors are multiplied through the equation; $CV_t / I_s e^{V_{1L}/V_t}$ then it is arranged to form the following nodal equations. The nodal equations realized by capacitors, transistors and current sources.

$$C\dot{V}_{1L} = \omega_0 C V_t e^{\frac{V_{2L}-V_{1L}}{V_t}} + z_1\omega_0 C V_t e^{\frac{V_{0L}-V_{1L}}{V_t}} - \frac{\omega_0}{I_{f1}} C V_t I_s e^{V_{1R}/V_t}$$

(10a)

$$C\dot{V}_{2L} = \omega_0 C V_t e^{\frac{V_{3L}-V_{2L}}{V_t}} + z_2\omega_0 C V_t e^{\frac{V_{0R}-V_{2L}}{V_t}} - \frac{\omega_0}{I_{f1}} C V_t I_s e^{V_{2R}/V_t}$$

(10b)

$$C\dot{V}_{3L} = \omega_0 C V_t e^{\frac{V_{4L}-V_{3L}}{V_t}} + z_3\omega_0 C V_t e^{\frac{V_{0L}-V_{3L}}{V_t}} - \frac{\omega_0}{I_{f1}} C V_t I_s e^{V_{3R}/V_t}$$

(10c)

$$C\dot{V}_{4L} = \omega_0 C V_t e^{\frac{V_{5L}-V_{4L}}{V_t}} + z_4\omega_0 C V_t e^{\frac{V_{0R}-V_{4L}}{V_t}} - \frac{\omega_0}{I_{f1}} C V_t I_s e^{V_{4R}/V_t}$$

(10d

$$\begin{aligned}C\dot{V}_{5L} &= b_0\omega_0 C V_t e^{\frac{V_{1R}-V_{5L}}{V_t}} + b_1\omega_0 C V_t e^{\frac{V_{2R}-V_{5L}}{V_t}} \\ &+ b_2\omega_0 C V_t e^{\frac{V_{3R}-V_{5L}}{V_t}} + b_3\omega_0 C V_t e^{\frac{V_{4R}-V_{5L}}{V_t}} \\ &- b_4\omega_0 C V_t + z_5\omega_0 C V_t e^{\frac{V_{0L}-V_{5L}}{V_t}} - \frac{\omega_0}{I_{f1}} C V_t I_s e^{V_{5R}/V_t}\end{aligned} \tag{10e}$$

$$y_R = I_s e^{V_{1R}/V_t} \quad (10f)$$

I_{f1}, I_{f2}, I_{f3}, I_{f4}, I_{f5}, I_{f6}, I_{f7}, I_{f8}, I_{f9}, I_{f10}, and I_{f11} are positive constants which are defined below equations:

$$I_{f1} = \omega_0 C V_t = I_s e^{V_{f1}/V_t} \quad (11a)$$

$$I_{f2} = z_1 \omega_0 C V_t = I_s e^{V_{f2}/V_t} \quad (11b)$$

$$I_{f3} = z_2 \omega_0 C V_t = I_s e^{V_{f3}/V_t} \quad (11c)$$

$$I_{f4} = z_3 \omega_0 C V_t = I_s e^{V_{f4}/V_t} \quad (11d)$$

$$I_{f5} = z_4 \omega_0 C V_t = I_s e^{V_{f5}/V_t} \quad (11e)$$

$$I_{f6} = b_0 \omega_0 C V_t = I_s e^{V_{f6}/V_t} \quad (11f)$$

$$I_{f7} = b_1 \omega_0 C V_t = I_s e^{V_{f7}/V_t} \quad (11g)$$

$$I_{f8} = b_2 \omega_0 C V_t = I_s e^{V_{f8}/V_t} \quad (11h)$$

$$I_{f9} = b_3 \omega_0 C V_t = I_s e^{V_{f9}/V_t} \quad (11i)$$

$$I_{f10} = b_4 \omega_0 C V_t \quad (11j)$$

$$I_{f11} = z_5 \omega_0 C V_t \quad (11k)$$

$$C\dot{V}_{1L} = I_{f1} e^{\frac{V_{2L}-V_{1L}}{V_t}} + I_{f2} e^{\frac{V_{0L}-V_{1L}}{V_t}} - I_s e^{V_{1R}/V_t} \quad (12a)$$

$$C\dot{V}_{2L} = I_{f1} e^{\frac{V_{3L}-V_{2L}}{V_t}} + I_{f3} e^{\frac{V_{0R}-V_{2L}}{V_t}} - I_s e^{V_{2R}/V_t} \quad (12b)$$

$$C\dot{V}_{3L} = I_{f1} e^{\frac{V_{4L}-V_{3L}}{V_t}} + I_{f4} e^{\frac{V_{0L}-V_{3L}}{V_t}} - I_s e^{V_{3R}/V_t} \quad (12c)$$

$$C\dot{V}_{4L} = I_{f1} e^{\frac{V_{5L}-V_{4L}}{V_t}} + I_{f5} e^{\frac{V_{0R}-V_{4L}}{V_t}} - I_s e^{V_{4R}/V_t} \quad (12d)$$

$$C\dot{V}_{5L} = I_{f6} e^{\frac{V_{1R}-V_{5L}}{V_t}} + I_{f7} e^{\frac{V_{2R}-V_{5L}}{V_t}} + I_{f8} e^{\frac{V_{3R}-V_{5L}}{V_t}} + I_{f9} e^{\frac{V_{4R}-V_{5L}}{V_t}} - I_{f10} + I_{f11} e^{\frac{V_{0L}-V_{5L}}{V_t}} - I_s e^{V_{5R}/V_t} \quad (12e)$$

(12a), (12b), (12c), (12d), and (12e) can be arranged as,

$$C\dot{V}_{1L} = I_s e^{\frac{V_{2L}+V_{f1}-V_{1L}}{V_t}} + I_s e^{\frac{V_{0L}+V_{f2}-V_{1L}}{V_t}} - I_s e^{V_{1R}/V_t} \quad (13a)$$

$$C\dot{V}_{2L} = I_s e^{\frac{V_{3L}+V_{f1}-V_{2L}}{V_t}} + I_s e^{\frac{V_{0R}+V_{f3}-V_{2L}}{V_t}} - I_s e^{V_{2R}/V_t} \quad (13b)$$

$$C\dot{V}_{3L} = I_s e^{\frac{V_{4L}+V_{f1}-V_{3L}}{V_t}} + I_s e^{\frac{V_{0L}+V_{f4}-V_{3L}}{V_t}} - I_s e^{V_{3R}/V_t} \quad (13c)$$

$$C\dot{V}_{4L} = I_s e^{\frac{V_{5L}+V_{f1}-V_{4L}}{V_t}} + I_s e^{\frac{V_{0R}+V_{f5}-V_{4L}}{V_t}} - I_s e^{V_{4R}/V_t} \quad (13d)$$

$$C\dot{V}_{5L} = I_s e^{\frac{V_{1R}+V_{f6}-V_{5L}}{V_t}} + I_s e^{\frac{V_{2R}+V_{f7}-V_{5L}}{V_t}} + I_s e^{\frac{V_{3R}+V_{f8}-V_{5L}}{V_t}} + I_s e^{\frac{V_{4R}+V_{f9}-V_{5L}}{V_t}} - I_{f10} + I_s e^{\frac{V_{0L}+V_{f11}-V_{5L}}{V_t}} - I_s e^{V_{5R}/V_t} \quad (13e)$$

The left hand side of output equation is $y_L = I_s e^{V_{1L}/V_t}$ (13f)

The left hand side of the fifth equation represents the currents flowing through a grounded capacitor, value C, having the voltages $\dot{V}_{5L}$. The term on the right hand side are combinations of currents through forward biased transistors and current sources. In the same way, right equations are determined in (14a), (14b), (14c), (14d), (14e), and (14f);

$$C\dot{V}_{1R} = I_s e^{\frac{V_{2R}+V_{f1}-V_{1R}}{V_t}} + I_s e^{\frac{V_{0R}+V_{f2}-V_{1R}}{V_t}} - I_s e^{V_{1L}/V_t} \quad (14a)$$

$$C\dot{V}_{2R} = I_s e^{\frac{V_{3R}+V_{f1}-V_{2R}}{V_t}} + I_s e^{\frac{V_{0L}+V_{f3}-V_{2R}}{V_t}} - I_s e^{V_{2L}/V_t} \quad (14b)$$

$$C\dot{V}_{3R} = I_s e^{\frac{V_{4R}+V_{f1}-V_{3R}}{V_t}} + I_s e^{\frac{V_{0R}+V_{f4}-V_{3R}}{V_t}} - I_s e^{V_{3L}/V_t} \quad (14c)$$

$$C\dot{V}_{4R} = I_s e^{\frac{V_{5R}+V_{f1}-V_{4R}}{V_t}} + I_s e^{\frac{V_{0L}+V_{f5}-V_{4R}}{V_t}} - I_s e^{V_{4L}/V_t} \quad (14d)$$

$$C\dot{V}_{5R} = I_s e^{\frac{V_{1L}+V_{f6}-V_{5R}}{V_t}} + I_s e^{\frac{V_{2L}+V_{f7}-V_{5R}}{V_t}} + I_s e^{\frac{V_{3L}+V_{f8}-V_{5R}}{V_t}} + I_s e^{\frac{V_{4L}+V_{f9}-V_{5R}}{V_t}} - I_{f10} + I_s e^{\frac{V_{0R}+V_{f11}-V_{5R}}{V_t}} - I_s e^{V_{5L}/V_t} \quad (14e)$$

The left hand side of output equation is $y_R = I_s e^{V_{1R}/V_t}$ (14f)

The realizations of current-mode 5th-order differential type class-AB log-domain elliptic lowpass filter circuit using (13a), (13b), (13c), (13d), (13e), (13f) and (14a), (14b), (14c), (14d), (14f) is shown in Fig. 1.

III. SIMULATION RESULTS

The proposed 5th-order log-domain elliptic lowpass filter was simulated with PSPICE simulation programs by using ideal transistor models, with β_F equal to 10000 (all parameters at default), and AT&T CBIC-U2 transistors. The circuit parameters are chosen as; $C = 60pF$, $V_{cc} = 2.5V$, $V_t = 25.6mV$, $f_0 = 5.75MHz$

$\alpha_{\min} > 40dB$, $\alpha_{\max} = 0.177dB$, $\omega_s / \omega_p = 1.37$,

The numerator coefficients:

$a_4 = 0.05546$, $a_2 = 0.3494$, $a_0 = 0.4772$,

The denominator coefficients:

$b_4 = 1.507$, $b_3 = 2.502$, $b_2 = 2.099$, $b_1 = 1.354$,

$b_0 = 0.4772$

The external current values:

$I_{f1} = 55{,}50uA$, $I_{f2} = 3.08uA$, $I_{f3} = 4.64uA$,

$I_{f4} = 18.68uA$, $I_{f5} = 23uA$, $I_{f6} = 26.49uA$,

$I_{f7} = 75.15uA$, $I_{f8} = 116.49uA$, $I_{f9} = 138.86uA$,

$I_{f10} = 83.64uA$, $I_{f11} = 19.98uA$

The gain response of the filter is shown in Fig. 2. Maximum ($\alpha_{\max} = 0.177dB$) passband ripple is shown in Fig.3.

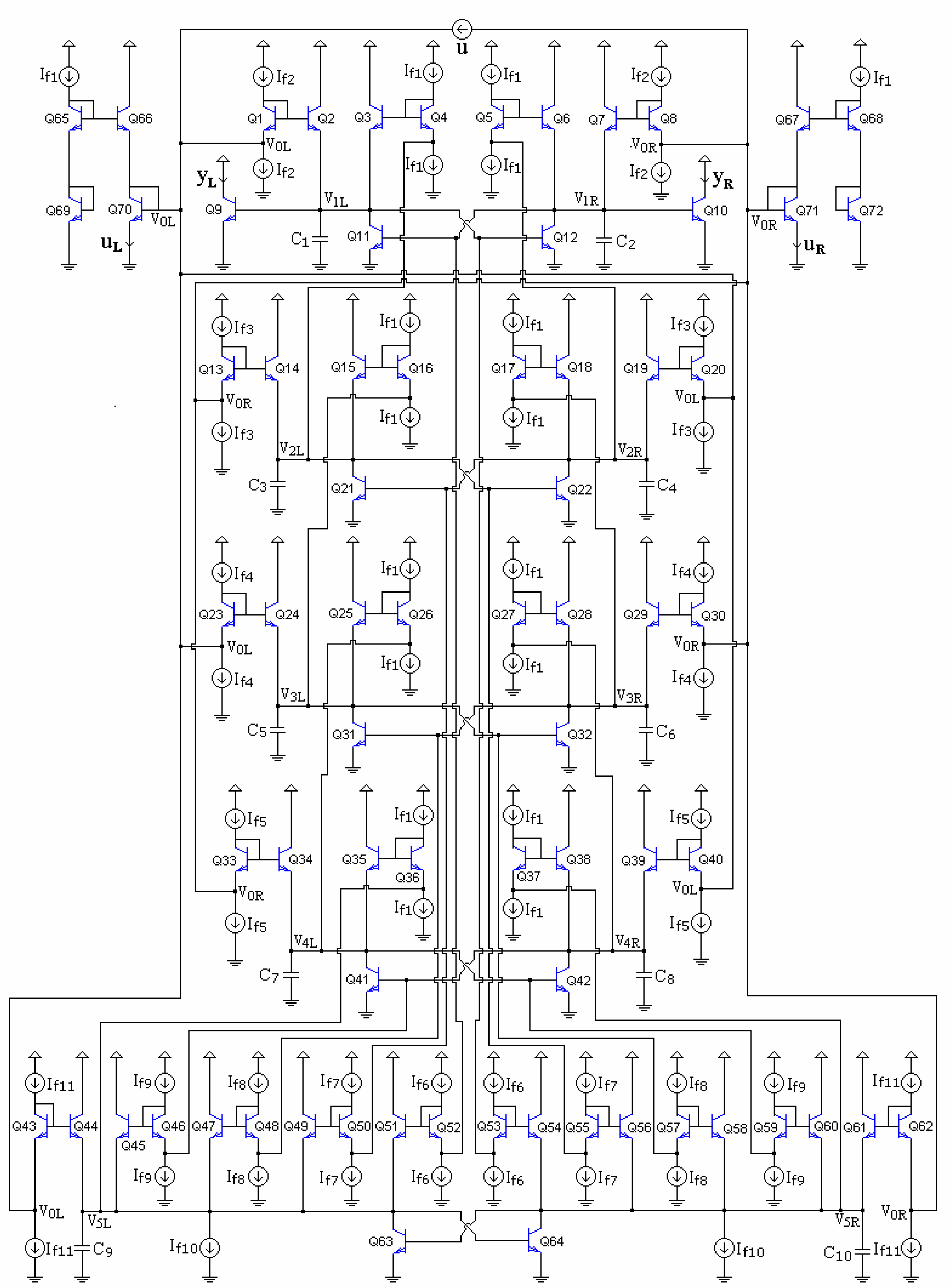

Figure 1. The current-mode 5th- order differential type class-AB log-domain elliptic lowpass filter

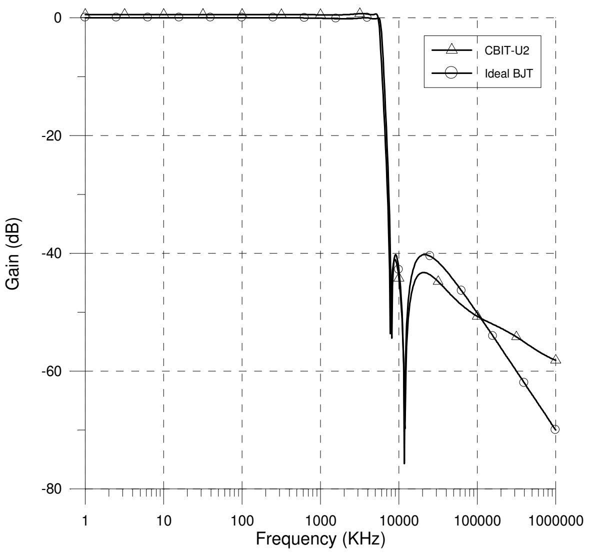

Figure 2. Gain response of the proposed filter

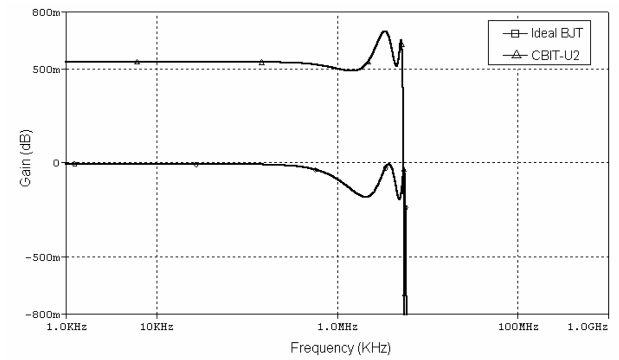

Figure 3. Maximum 0.177 dB passband ripple

The cut-off frequency of the filter can be electronically tuned by changing external currents as shown in Fig. 4. The cut-off frequency was tuned from *2MHz* to*20MHz*. Filter step response is shown in Fig. 5. Dynamic range of the filter is greater than *60dB*,THD(%) is less than *1*.

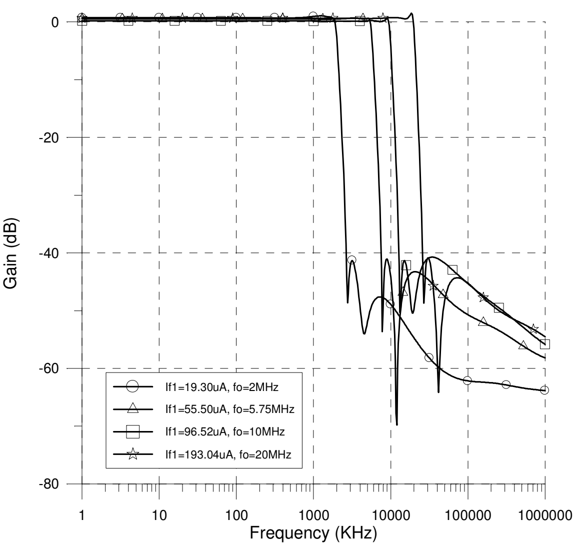

Figure 4. Tuning characteristics of the proposed filter

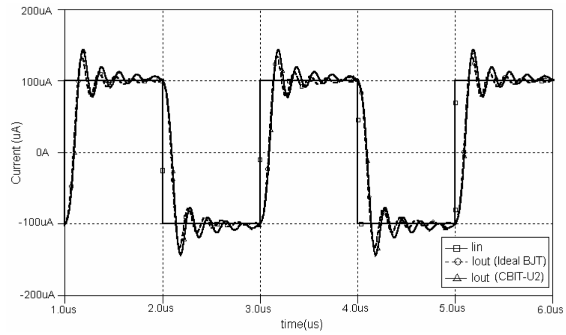

Figure 5. Step response of the filter

IV. CONCLUSION

A new current-mode 5th-order differential type class-AB log-domain elliptic lowpass filter structure is proposed in this work. The novelty of this study is a successful application of state-space synthesis method to realize 5th-order current-mode differential class-AB log-domain elliptic filter for video frequency applications. The filter parameters can be electronically tuned by changing external currents. It has a greater bandwidth due to inherently current-mode and log-domain operation. It is suitable for low voltage/power applications. The proposed filter provides large dynamic range and lower THD values due to realizing linear system with inherently nonlinear circuit building blocks and companding properties. It is suitable for VLSI technologies due to employing only BJTs and grounded capacitors. PSPICE simulations are provided to confirm the theoretical analysis. Tolerable differences are observed that realization of this filter in simulation has provided satisfactory results.

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