Analysis and Design of Voltage Controlled LC Amplifiers using Current-Feedback Amplifiers

Ivailo M. Pandiev[1]

Abstract - **This paper discusses the development of a specific type of voltage controlled LC amplifier using a current-feedback amplifier (CFA). The center frequency of the proposed selective amplifier is controlled by applying a voltage to the parallel resonator with varactor capacitive branch. The main advantage of this new configuration is the insignificant influence of the load over the parameters of the amplifier. Some recommendations for designing this kind of analogue circuit are given based on simulation results and symbol analysis of the transfer function. To confirm the validity of the design procedure, simulation results are compared with measurements of the electrical parameters in a practical LC amplifier, where is found good agreement between simulations and measurements.**

Keywords – **LC amplifier, Current-Feedback Amplifier (CFA), Frequency control, Varactor tuning, PSpice simulations.**

I. INTRODUCTION

The voltage controlled LC amplifiers (LC-tuned amplifiers) and LC oscillators (VCOs) are essential building blocks of contemporary communication systems [2]-[4]. Simultaneously the new CFA are gaining popularity as alternative building blocks for analogue signal processing because of offering advantages over the conventional op amps. The main advantages are wide bandwidth which is relatively independent of the closed-loop gain, very high slew rate and simplicity of realization of various functions with the least possible number of external passive components.

The symbolic representation of CFA based on the second-generation current conveyor (CCII) is shown in Fig. 1. The main difference between the CFA and the CCII is the unity gain voltage buffering of the *out1* compensation terminal of the CCII to obtain the *out2* output terminal of the CFA [5]. The output terminal of the CFA is low impedance (voltage source) and the compensation terminal is high impedance (current source). This high impedance in the terminal *out1* allows connect a parallel resonator (LC tank) with varactor capacitive branch. In [8] is proposed LC amplifier using CFA with compensation terminal and LC tank. This circuit simple can be converted into LC-tuned amplifier by replacing the capacitor in the resonator with series back-to-back connection of two varactors. This paper presents a new LC-tunrd amplifier using CFA with compensation terminal and resonator consists of inductor and series connection of varactors. The proposed analogue circuit has the following advantages over the single transistor LC amplifier: (1) the insignificant influence of the load over the parameters of the LC tank; (2) ability for independent fine tuning of voltage gain, Q factor, and center frequency; (3) high input and low output resistance.

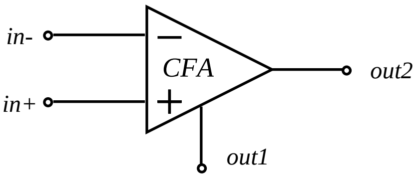

Fig. 1. The CFA symbol

II. CIRCUIT DESCRIPTION

The proposed circuit of the voltage controlled LC amplifier is shown in Fig. 2. It is based on a CFA with compensation terminal and with negative voltage feedback, implemented with the resistors R_1 and R_2. This configuration achieves higher input impedance compared to the inverting amplifier. The capacitor C_1 made the voltage feedback frequency-dependence. A parallel LC tank was connected to the additional op amp compensation terminal (*out1* in Fig. 2), where the input resistance is very high. The LC tank consists of inductor L and series back-to-back connection of two varactors (DC_1 and DC_2). This connection allows lower capacitance at high dc control voltages (U_{ctrl}) compared to maintaining the tuning ratio of a single varactor. The back-to-back varactor connection also helps reduce distortion and effect of mounting capacitances.

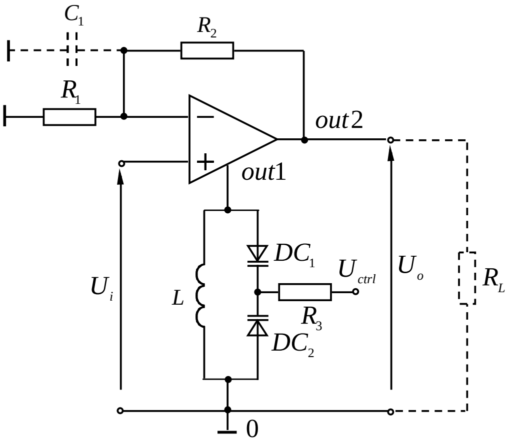

Fig. 2. LC-tuned amplifier using CFA with correction terminal

The analysis of the proposed LC amplifier was performed using nodal voltage method and the equivalent circuit shown in Fig. 3. In the equivalent circuit CFA is substituted with

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[1] Ivailo M. Pandiev is with the Faculty of Electronics from Technical University of Sofia, Kliment Ohridski 8, 1000 Sofia, Bulgaria. E-mail: ipandiev@tu-sofia.bg

linear macromodel which represent the small-signal behavior of the real devices [9]. This model includes the following elements: ideal input and output buffer (voltage follower); controlled current source (I_{in}); resistance of the inverting input (R_{in}); active and reactive components (R_t and C_t) of the transmission resistance z_t; output resistance (R_o). The inductor L of the resonator can be presented with serial-parallel equivalent circuit, as shown in Fig. 3. The active resistance r_L of the inductor determines the losses, and C_a is the parasitic capacitance of the pins. The varactors are substituted with the parallel equivalent circuits as shown in Fig. 3, where $C_{v(1,2)}$ is a varactor capacitance, $r_{c(1,2)}$ is a series resistance determines the losses and $C_{p(1,2)}$ is a mounting capacitance between pins. According to the SPICE model, varactor capacitance $C_{v(1,2)}$ is a function of the applied reverse dc voltage (U_{ctrl}) and can be expressed as follows:

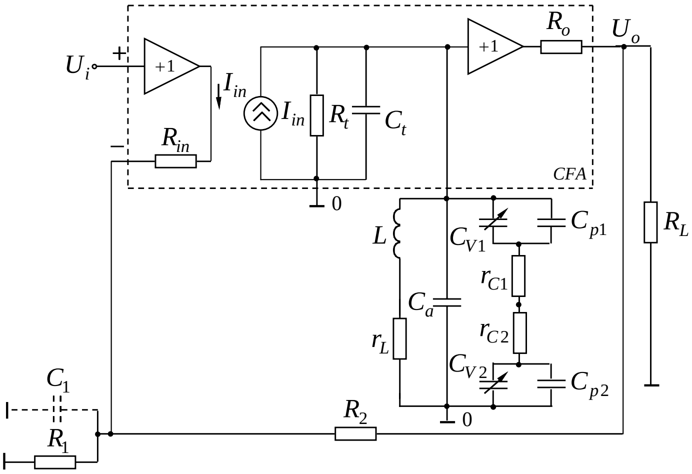

Fig. 3. Equivalent circuit of the LC-tuned amplifier using CFA with correction terminal.

$$C_v = \frac{C_{JO}}{\left(1 + \frac{U_{ctrl}}{U_J}\right)^m} + C_p \,, \tag{1}$$

where C_{JO} is a zero-bias junction capacitance, U_J – junction potential, and m – grading coefficient (0,5 by default).

The Y-matrix of the circuit with load R_L was composed using the well-known formulas introduced in [1], and after the transformations is obtained the following expression for the transfer function:

$$\dot{A}_U = \frac{1 + \frac{R_2}{R_1} + j\omega C_1 R_2}{\left[1 + \frac{R_2}{R_{re}}\left(1 + \frac{R_{in}}{R_1} + \frac{R_{in}}{R_2}\right)\left(1 + \frac{R_o}{R_L}\right)\right]\left[1 + jQ_e\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right)\right]} \,, \tag{2}$$

where equivalent quality factor of the amplifier is

$$Q_e = \frac{R_2\left(1 + \frac{R_{in}}{R_1} + \frac{R_{in}}{R_2}\right)\left(1 + \frac{R_o}{R_L}\right)}{\rho\left[1 + \frac{R_2}{R_{re}}\left(1 + \frac{R_{in}}{R_1} + \frac{R_{in}}{R_2}\right)\left(1 + \frac{R_o}{R_L}\right)\right]} \,, \tag{3}$$

characteristic resistance of the LC tank is

$$\rho = \sqrt{L / C_e} \,, \tag{4}$$

equivalent resonance resistance of the LC tank is

$$R_{re} = R_{rL} \,||\, R_{rC} \,||\, R_3 \,||\, R_t \tag{5}$$

($R_{rL} = \rho^2 / r_L$, $R_{rC} = \rho^2 / r_{C_e}$, $r_{C_e} = r_{C_1} + r_{C_2}$),

center (resonance) frequency is

$$\omega_o = 1 / \sqrt{LC_e} \,, \tag{6}$$

and equivalent capacitance is

$$C_e = C_{V_e} + C_t + C_a + C_M \,, \tag{7}$$

where $C_{V_e} = C_{V1} \,||\, C_{V2}$ is equivalent varactor capacitance, and C_M is the mounting capacitance.

According to Eq. (2) for the center frequency $\omega = \omega_o$, the voltage gain is maximum, e.g.

$$\left|\dot{A}_U(\omega_o)\right| = A_U = \frac{\sqrt{\left(1 + \frac{R_2}{R_1}\right)^2 + (\omega_o C_1 R_2)^2}}{1 + \frac{R_2}{R_{re}}\left(1 + \frac{R_{in}}{R_1} + \frac{R_{in}}{R_2}\right)\left(1 + \frac{R_o}{R_L}\right)} \,. \tag{8}$$

For the frequencies near to the resonance, e.g. $\omega \approx \omega_o$, the pass band $B_{0,7}$ of the amplifier can be calculated by:

$$B_{0,7} = f_o / Q_e \,. \tag{9}$$

III. LC AMPLIFIER DESIGN PROCEDURE

The design method of voltage controlled LC amplifier suggested in this paper is based on the above analytical formulas as well as of the design methodology presented in [3]. The circuit elements are calculated using pre-defined: range of frequencies in which the LC amplifier should be tuned ($f_{o_{min}}$, $f_{o_{max}}$), voltage gains ($A_{U_{min}}$, $A_{U_{max}}$) at those frequencies, and *instantaneous* bandwidth range ($B_{0,7_{min}}$, $B_{0,7_{max}}$) the amplifier has within the tuning range or quality factors ($Q_{e_{\min}}$, $Q_{e_{\max}}$).

The design procedure for the LC amplifier shown in Fig. 2, is based on the following sequence:

A. Center frequency, Q factor and voltage gain

The amplifier's average center frequency, Q factor, and voltage gain is given by

$$f_{o_{av}} = \sqrt{f_{o_{min}} . f_{o_{max}}} \,, \tag{10}$$

$$B_{0,7_{av}} = \sqrt{B_{0,7_{min}} . B_{0,7_{max}}} \,, \tag{11}$$

$$Q_{e_{av}} \geq f_{o_{av}} / B_{0,7_{av}} \,, \tag{12}$$

$$A_{U_{av}} = \sqrt{A_{U_{min}} . A_{U_{max}}} \,. \tag{13}$$

B. Current feedback amplifier

The CFA is selected according to the following conditions:

- Presence of an additional correction terminal of the IC with high impedance;
- Unity gain frequency $BW > (1{,}2 \div 2) f_{o_{\max}}$;
- High transfer resistance, so that for selected LC elements to accomplish the condition $R_t >> R_{rL} \,||\, R_{rC} \,||\, R_3$.

C. Inductor L

The inductance of the inductor for the LC tank is selected. The following empirical values for the inductance can be recommended according to the center frequency:

- $L \geq 100\mu H$ for $f_{o_{av}}$ within $100kHz \div 1MHz$;
- $L =$ $10\mu H \div 100\mu H$ for $f_{o_{av}}$ within $1 \div 10MHz$;
- $L \leq 10\mu H$ for $f_{o_{av}} \geq 10MHz$.

The inductor with quality factor Q_L larger than the amplifier equivalent quality factor $Q_{e_{av}}$ (Eq. (12)) is selected. The values of the elements forming the inductor serial-parallel equivalent circuit (r_L, L and C_a), shown on Fig. 3, are determined empirically.

D. Varactors

The tuning device has to provide a variable capacitance within a range:

$$C_{Ve_{min}} = \frac{1}{\left(2\pi f_{o_{max}}\right)^2 L} - \left(C_t + C_a + C_M\right), \tag{14a}$$

$$C_{Ve_{max}} = \frac{1}{\left(2\pi f_{o_{min}}\right)^2 L} - \left(C_t + C_a + C_M\right), \tag{14b}$$

where C_M is the mounting capacitance (usually between 2 and 10pF). According to equations (14a) and (14b), the smallest capacitance tunes the highest tunable frequency, $f_{o_{max}}$, and the largest capacitance the lowest one, $f_{o_{min}}$. The varactor with $\left(C_{d_{\min}} / 2\right) \leq C_{Ve_{\min}}$ and $C_{d_{\max}} / 2 \geq C_{Ve_{\max}}$ is selected, where [$C_{d_{min}}$, $C_{d_{max}}$] is the capacitance range of the tuning element. The average value of the varactor capacitance can be calculated by

$$C_{Ve_{av}} = \frac{1}{\left(2\pi f_{o_{av}}\right)^2 L} - \left(C_t + C_a + C_M\right). \tag{14c}$$

E. Equivalent resistance R_{re} and tuning terminal resistance R_3

$$\rho_{av} = \sqrt{\frac{L}{C_t + C_{Ve_{av}} + C_a + C_M}}\ , \tag{15}$$

$$R_{rL} = \rho_{av}^2 / r_L\, , \tag{16a}$$

$$R_{rC} = \rho_{av}^2 / r_{C_e}\, , \tag{16b}$$

where $r_{C_e} = r_{C_1} + r_{C_2}$.

$$R_{re}^{'} = R_{rL} \,||\, R_{rC} \,||\, R_t\, , \tag{17a}$$

$$R_3 \geq (3 \div 5) R_{re}^{'}\, , \tag{17b}$$

$$R_{re} = R_{rL} \,||\, R_{rC} \,||\, R_3 \,||\, R_t\, . \tag{17c}$$

F. Feedback resistors R_1 and R_2

$$R_1 = \left(\rho_{av} Q_{e_{av}} - R_{in} A_{U_{av}}\right) / A_{U_{av}}\, , \tag{18a}$$

$$R_2 = \frac{\rho_{av} Q_{e_{av}}}{\left(1 - \dfrac{\rho_{av} Q_{e_{av}}}{R_{re}}\right)\left(1 + \dfrac{R_{in}}{R_1}\right)}\, . \tag{18b}$$

The calculated values for the resistors R_1 and R_2 according to equations (18a) and (18b) have to be consistent with the values obtained by
$R_1 \geq R_{in}$, and $R_2 \leq 1 / \left\lfloor 2\pi f_{o_{\max}} C_t \left(1 + R_{in} / R_1\right)\left(1 + R_o / R_L\right)\right\rfloor$ [9].

G. Capacitance C_1

In the cases where it is necessary to obtain greater voltage gain for a given quality factor, and feedback resistors, a capacitance C_1 is connected in parallel to the R_1. The capacitance C_1 can be calculated by

$$C_1 = \frac{\sqrt{A_{U_{av}}^2 \left[1 + \dfrac{R_2}{R_{re}}\left(1 + \dfrac{R_{in}}{R_1} + \dfrac{R_{in}}{R_2}\right)\right]^2 - \left(1 + \dfrac{R_2}{R_1}\right)^2}}{\omega_{o_{av}} R_2}\, . \tag{19}$$

IV. LC AMPLIFIER DESIGN EXAMPLE

In this section a specific design of a voltage controlled LC amplifier will be performed following the previously described technique. The initial design requirements and specifications are given in Table I.

TABLE I
DESIGN SPECIFICATIONS

$f_{o_{min}}$	3MHz
$f_{o_{max}}$	12MHz
$A_{U_{av}}$	20 ($f_{o_{av}} = 6MHz$, $R_L = 500\Omega$)
$Q_{e_{\max}}$	12
$Q_{e_{\min}}$	8

The systematic design approach provided in Section III is next applied. First, from equations (10), (11), (12) and (13) the design center frequency $f_{o_{av}}$, voltage gain $A_{U_{av}}$ at this frequency, and *instantaneous* bandwidth range $B_{0,7_{av}}$ is determined. The circuit was implemented using AD844A [6] with the following electrical parameters: $BW = 60MHz$, $R_t = 3M\Omega$, $C_t = 4{,}5pF$, $R_{in} = 50\Omega$ and $R_o = 15\Omega$. For the LC tank is selected inductor $L = 10\mu H$ ($Q_L \approx 200$). The values of the elements forming the inductor serial-parallel equivalent circuit are: $r_L = 1{,}97\Omega$, $L = 9{,}83\mu H$ and $C_a = 890\,fF$.

Next, making use of (14a), (14b), and (14c) the capacitances are: $C_{Ve_{min}} = 17{,}6pF$, $C_{Ve_{max}} = 282pF$, and $C_{Ve_{av}} = 70{,}4pF$. Once the previous parameters are determined a tuning varactor BB112 [7] is placed in the resonant tank circuit for frequency tuning. The parameters $R_3 = 200k\Omega$, $R_1 = 500\Omega$ and $R_2 = 2{,}2k\Omega$ is calculated using (17c), (18a) and (18b). Finally the parameter $C_1 = 220pF$ is obtained using equation (19). The design parameter values and their variation range obtained through the design technique are shown in Table II with the parameters of the LC-tank for the smallest and the highest tunable frequency.

TABLE II
LC-TUNED AMPLIFIER DESIGN PARAMETERS

f_o	6MHz, 3MHz $\le f_o \le$ 12MHz
A_U	21.4, 9.1 $\le A_U \le$ 42 ($R_L = 500\Omega$)
Q_e	8.65, 8.94 $\le Q_e \le$ 11.23
ρ	376Ω, 188 Ω ≤ ρ ≤ 753.7 Ω
Q_{LC}	76, 38 $\le Q_{LC} \le$ 152
R_{re}	28.5kΩ, 11.8kΩ $\le R_{re} \le$ 114kΩ

The practical LC-tuned amplifier is simulated making use of the op amp macromodel AD844A/AD from standard PSpice library. The AD844A/AD is fourth level of complexity model, providing maximum accuracy of the modeled electrical parameters. The results of the simulations and measurements of the amplifier are given in Fig. 4 for different control voltages. As can be seen it meets the initial requirements given in Table I and the error is smaller than 5%. The total harmonic distortion of the output signal U_o is less than 4% ($U_{im} = 100mV$, $f_o = 6MHz$, and $R_L = 500\Omega$). Table III resumes the performance of the LC-tuned amplifier shown in

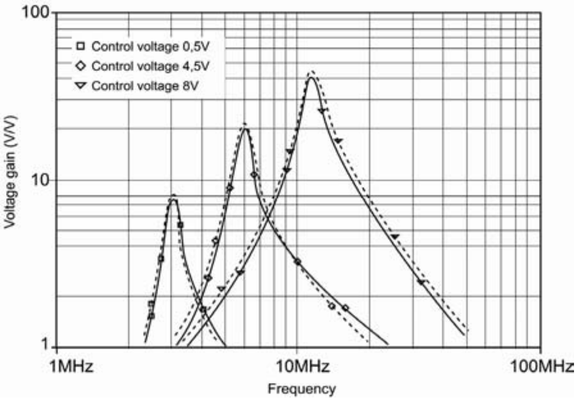

Fig. 4. Voltage gain versus frequency for various control voltages: simulations and measurements (dashed line).

TABLE III
LC-TUNED AMPLIFIER MEASURED RESPONSE

$f_{o_{min}}$	3MHz
$f_{o_{max}}$	12MHz
$A_{U_{av}}$	20.1 ($f_{o_{av}} = 6MHz$, $R_L = 500\Omega$)
$Q_{e_{\max}}$	12.29
$Q_{e_{\min}}$	9.06

VI. CONCLUSIONS

A voltage controlled LC amplifier using CFA with additional compensation terminal has been presented. The center frequency of the proposed circuit can be changed by applying a dc control voltage to the parallel resonator with varactor capacitive branch. A systematic procedure to design this type of analogue circuit based on symbol analysis of the transfer function has been presented. Validity of the design procedure have been tested by comparing simulations with measurements of the electrical parameters in a practical LC amplifiers, where is found that simulation and measurement results are in good agreement.

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