VOLTAGE CONTROLLED LC OSCILLATOR WITH CURRENT FEEDBACK AMPLIFIER

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A voltage controlled LC-oscillator is proposed in the paper, realized by a current-feedback operational amplifier (CFA) with an additional terminal, used for control of some amplifier parameters. A parallel resonant circuit is connected to this amplifier terminal, consisting of an inductor and two varicaps, their capacitance being controlled by dc voltage. In order to ensure the selfoscillation in the whole range of frequency variation, an oscillator design approach is developed, based on simulation testing results. An example is given for the designed according to the developed methodology LC oscillator circuit, realized using CFA AD844A. The results of the simulation testing of the oscillator and of the performed physical experiment are presented.

Keywords: voltage controlled oscillator, current-feedback operational amplifier, LC selective systems

1. INTRODUCTION

The voltage controlled oscillators are widely used in various areas of electronics - communication equipment, PLL circuits, automatic control circuits, etc. Such high-frequency oscillators are often realized as LC oscillators. An oscillator of this type is described in [1]. A current-feedback amplifier (CFA) is used, based on second generation current converters (CCII) with a buffer connected to the output. In addition, the amplifier has an extra port used for control of some of its parameters. Such CFA offers new possibilities: very high output resistance (of the order of several MΩ), an additional port allowing to introduce a parallel LC circuit between this port and the ground. Since the main output (after the buffer) is characterized by a low output resistance, the load, connected to this output, can be of low

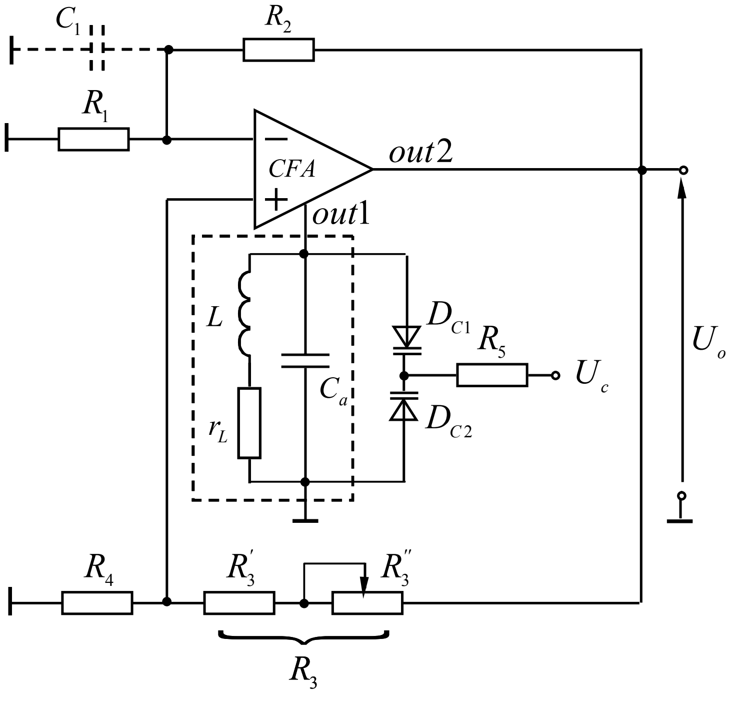

Fig. 1. Voltage controlled LC oscillator with CFA

value without a significant influence on the quality factor of the LC resonant circuit.

In the VCO realization, based on the described oscillator, the capacitor in the LC circuit can be replaced by two oppositely coupled varicaps in series, whose capacitance is controlled by DC voltage. A variant of the proposed circuit is shown in Fig. 1. The operational amplifier in this circuit is enveloped by two feedbacks – one negative, realized by the resistors R_1, R_2 and the capacitor C_1 compensating the phase distortions in the closed loop, and one positive, realized by the resistors R_3 and R_4. These resistors can be potentiometers for tuning of the positive feedback depth until the amplitude selfoscillating condition is fulfilled. Simultaneously, the amplitude of the output signal can be tuned by these resistors. The methodology described in [1] is used for value determination of these elements.

When for the minimal value of the tuned oscillator frequency the used varicaps require controlling voltage magnitude less than the signal amplitude on the LC circuit, it is necessary to lower this amplitude to avoid the turn-on of some of the varicaps. This can be achieved for example by connecting the LC circuit to the amplifier port *out*1 by a step-down transformer (Fig. 2). In fact, the resonant system is a two-loop system because the output capacitance in the CFA additional port is connected to the primary winding of the transformer and parasitic capacitance between both windings exerts effect too.

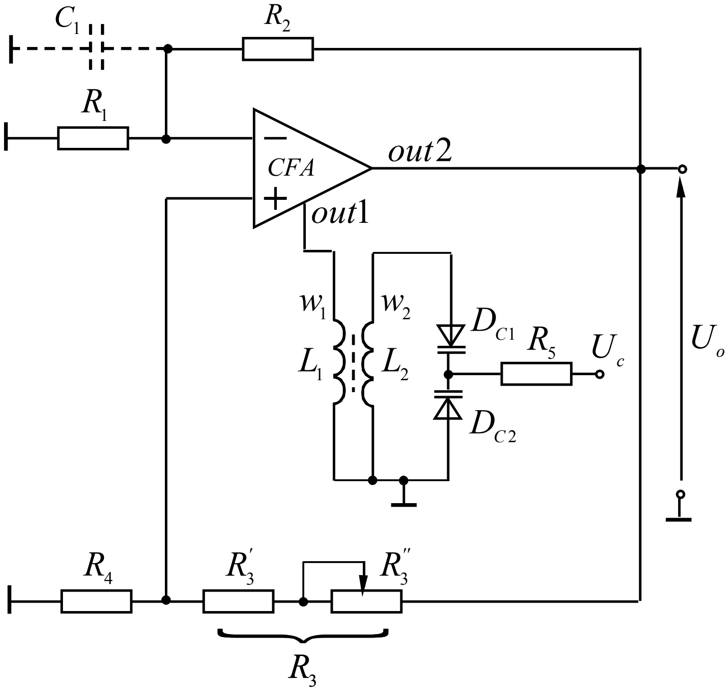

Fig. 2. Voltage controlled LC oscillator with CFA and step-down transformer

2. DESIGN PROCEDURE

The described here design methodology for the LC-voltage controlled oscillator, consists of two parts: preliminary hand calculations and computer simulations for the optimal value determination of the outer elements. The basic technical parameters used for the design of the circuit according to the typical configuration shown in Fig. 1, are: working range ($f_{G\,min}$, $f_{G\,max}$) of the frequency f_G and control voltage range; output voltage amplitude U_{om} for the given load resistance R_L, and sometimes other parameters such as supply voltage, sensitivity (MHz/V), nonlinear distortion coefficient. Using the results in [1], the design of the circuit is performed in the following sequence:

1. CFA is selected, which satisfies the conditions:
   - Existence of an additional port between the first stage (controlled current source) and the second stage (voltage follower) in the integrated circuit;
   - Unity gain frequency $BW > (2 \div 5) f_G$;
   - Large transresistance so that for selected LC elements the requirement $R_t >> R_{ro}$ (or $R_{re} \approx R_{ro}$) is met, where R_{ro} is the resonant circuit resistance;
2. The power supply of the circuit $U_{CC} \geq (1{,}5 \div 2) U_{om}$ is selected.
3. Varicaps for the resonant circuit are selected. For this purpose a tentative value is selected in the frequency range from 1MHz to several tens of MHz that might be for example $1\mu H \div 100\mu H$ (larger inductance values may lead to reducing the inductor quality factor Q_L).

Since two identical varicaps of capacitance C_D are connected in series in the resonant circuit, it is necessary that their equivalent capacitance $C_V = C_D / 2$ can be varied within the range, limited by the values:

$$\text{(1a)} \quad C_{V\min} \leq \frac{1}{\left(2\pi f_{G\max}\right)^2 L} - \left(C_t + C_a + C_M\right);$$

$$\text{(1b)} \quad C_{V\max} \geq \frac{1}{\left(2\pi f_{G\min}\right)^2 L} - \left(C_t + C_a + C_M\right),$$

where C_M is the mounting capacitance (usually between 2pF and 10pF) and C_t is the inner equivalent capacitance of the CFA.

Depending on the manner of obtaining the control voltage, other varicap parameters can be taken into account during their selection, such as sensitivity, initial capacitance, reverse current, etc.

After the selection of the proper varicap type, the exact inductance value is calculated, using for example formula (1b). In addition the parameters of the elements of the parallel-series inductor equivalent circuit (r_L, L and C_a) in Fig. 1 are determined and this is best achieved experimentally.

4. The equivalent resistance of the resonance LC-circuit R_{re} and the resistance R_5 are calculated:

$$\text{(2)} \qquad \rho_{min} = \sqrt{\frac{L}{C_t + C_{V\,max} + C_a}};$$

$$\text{(3a)} \quad R_{ro} = \frac{\rho_{min}^2}{r_L}; \quad \text{(3b)} \quad R'_{re} = R_t \,||\, R_{ro};$$

$$\text{(4)} \qquad R_5 \geq (5 \div 10) R'_{re};$$

$$\text{(5)} \qquad R_{re} = R_t \,||\, R_{ro} \,||\, R_5 .$$

5. Tentative values of the resistors R_1 and R_2 are calculated using the formulas (6a) and (6b) (under the condition that the capacitor is not taken into consideration):

(6a) $R_1 = (2 \div 10)R_{in}$;

(6b) $$R_2 = \frac{1}{2\pi f_{G\,min} C_t \left(1 + \frac{R_{in}}{R_1}\right)\left(1 + \frac{R_o}{R_L}\right)}.$$

The obtained resistor values of R_1 and R_2 from (6a) and (6b) have to be in compliance with the recommended values for feedback resistors in the datasheets for the selected CFA.

6. The initial value for the capacitor C_1 is determined:

$$C_1 = \frac{\rho_{min}\sqrt{\left(1 + \frac{R_{in}}{R_1}\right)\left(1 + \frac{R_2}{R_1}\right)}}{2\sqrt{R_{in}R_2}}\left(C_{V\,max} + C_t + C_a + C_M\right). \tag{7}$$

7. The maximal gain $A^{-}_{F\,max}$ is determined using the expression [1]:

$$A^{-}_{F\,max} = \frac{1 + \frac{R_2}{R_1} + \frac{R_o}{R_{re}}\left[1 + \frac{R_2}{R_3}\left(1 + \frac{R_{in}}{R_1} + \frac{R_{in}}{R_2}\right)\right]}{1 + \frac{R_2}{R_{re}}\left(1 + \frac{R_{in}}{R_1} + \frac{R_{in}}{R_2}\right)\left(1 + \frac{R_o}{R_2} + \frac{R_o}{R_3} + \frac{R_o}{R_L}\right)}. \tag{8}$$

8. Approximate values of the resistors R_3 and R_4 are determined from the expressions:

(9a) $R_3 = (1{,}5 \div 2{,}5)R_2$;

(9b) $R_4 = \frac{\beta^{+}}{1 - \beta^{+}} R_3$, where $\beta^{+} = \frac{0{,}6 \div 0{,}8}{A^{-}_{F\,max}}$.

9. Simulation testing is performed with positive and negative feedback for the selective LC-amplifier, which is the base for realization of the LC-oscillator. According to the procedure described in [1], frequency and statistical analyses are performed in the OrCAD PSpice environment. The statistical analysis has to be made for the lowest frequency in the realized range of the VCO for obtaining the optimal values of the elements R_1, R_2, R_3, R_4 and C_1.

This is the worst case, since for one and the same value of the resonant circuit inductor the lowest frequency is obtained for the highest capacitance value of the varicaps and then the resonant resistance has the lowest value and as seen from the expression for $\left|\beta^{+}\right|\left|\dot{A}^{-}_{F}\right|$ given in [1], it is most difficult to satisfy the amplitude condition. For all higher frequencies the selfoscillation is ensured (provided that the phase condition is also satisfied for the whole frequency range).

As a result of the performed computer simulations, the optimal values of the elements R_1, R_2, R_3, R_4 and C_1 are obtained. Next the gain $A^{-}_{F\,max}$ is recalculated according to the expression (8) and the resistance value of R_3 is determined from the expression:

(10) $R_3 = \dfrac{1-\beta^+}{\beta^+} R_4$, where $\beta^+ = \dfrac{1{,}2 \div 2}{A^-_{F\max}}$.

10. Verification of the designed electronic circuit is performed. Using the obtained element values, a time-domain analysis is accomplished in the OrCAD PSpice environment for the maximal capacitance value of the varicaps. As a result of the computer simulations, the amplitude of the output voltage, the frequency and the coefficient of nonlinear distortions are determined. These values are compared with the corresponding experimentally obtained parameters.

When the circuit in Fig. 2 is used, the transformer ratio $n = w_2 / w_1$ (w_1 and w_2 are the number of windings of the primary and secondary windings correspondingly) has to be selected with its maximal possible value ensuring the necessary signal decreasing. Then the transferred to the primary winding capacitance of the varicaps ($C'_{V,e} = n^2 C_{V,e}$) has the maximal possible value and the influence of the parasitic capacitances on it is minimal. Otherwise, if the value n is chosen less than the necessary one, the transferred to the primary winding capacitance of the varicaps might decrease to such an extent that it would be comparable or even less than the parasitic capacitances, making the frequency control in the given range impossible.

The transfer coefficient k also exerts impact on the two-loop circuit parameters. It is recommended for this parameter to be large enough to accomplish an effective frequency control, but not to exceed the values, when the resonant characteristics acquire two peaks. In the last case it is possible that indetermination may occur for the generation frequency.

It is necessary to take into account when selecting the inductance values of L_1 and L_2 that the larger value of L_1 leads to a larger value of the resonant resistance in the primary winding and the condition for selfoscillation is satisfied easily. However, when the inductance value is large, the quality factor may decrease and then the resonant frequency will be lower for the same capacitance value. Hence, a compromise solution has to be chosen for each particular case. The value of L_2 is determined from the selected values of n and L_1.

3. EXAMPLE FOR DESIGN OF VOLTAGE CONTROLLED LC-OSCILLATOR AND RESULTS FROM ITS EXPERIMENTAL EXAMINATION

The proposed methodology is illustrated by the design of voltage controlled LC-oscillator working in the frequency range from 3MHz to 9 MHz. It is built using the circuit shown in Fig. 1 with CFA AD844A [2]. This OpAmp is selected since its bandwidth $BW = 60MHz$ is significantly larger than the higher cutoff frequency, its transresistance $R_t = 3M\Omega$ is much greater than the realizable values of the resonant resistance of the resonant circuit and the inner equivalent capacitance $C_t = 4{,}5pF$ is much lover than the expected value for the varicaps. The inductance value in the resonant circuit is chosen in the range 1μH - 10μH. Using formulas (1a) and (1b), the approximate values $C_{V\min} = 18{,}8pF$ and $C_{V\max} = 275pF$ are obtained. Based on these values, the varicap BB112 is chosen with a minimal capacitance value $C_{D\min} = 25pF$ for the control voltage $V_C = 8{,}5V$ and a maximal value $C_{D\max} = 600pF$ for $V_C = 0{,}5V$ [3].

Using calculations according to the proposed methodology, the parameters of the resonant circuit given in Table 1 have been determined. The quality characteristics of the inductor are obtained experimentally.

Table 1.

L	Q_L	r_L	C_a	C_M	$C_{V\max}$	$\rho_{\min}$	R_{ro}	R_{re}
10μH	80	1,97Ω	4,978pF	2pF	300pF	180,5Ω	16,53kΩ	16,44kΩ

The initial values of the outer elements, determined on the base of the proposed design methodology, are given in Table 2.

Table 2.

R_1	R_2	R_3	R_4	R_5	C_1	$A^-_{F\,max}$	β^+
500Ω	1kΩ	2,2kΩ	200Ω	100kΩ	100pF	2,81	0,083

In order to ensure the work in the possibly steepest part of the phase frequency characteristic of $\beta^+ A^-_F$ and respectively to achieve the best frequency stability, the element values are optimized by a statistical (Monte Carlo) analysis with given tolerance of the values ±50% and 100 simulation runs. The optimal variant is selected when the maximum of A^-_F is achieved for the frequency closest to the minimal working frequency and the corresponding phase angle has a minimal value (<10°). The numerical values of the basic parameters of the resonance amplifier and the parameter values of the outer elements are given in Table 3 for the chosen optimal variant (variant 26).

Table 3.

Variant	R_1, Ω	$R_2, k\Omega$	$R_3, k\Omega$	R_4, Ω	C_1, pF	$A^+_{F\,max}$	$f_{o\min}$, MHz	$\varphi_o, {}^\circ$	A^-_F calc.	A^-_F sim.
26	254	1	3	210	51,63	6,28	2,9	1,5	4,6	4,67

For the obtained element values according to formula (8) the value of $A^-_{F\max}$ ($A^-_{F\max} = 4{,}61$) and the value of R_3 are recalculated: $R_3 = 600\Omega$ for $\beta^+ = 1{,}2 / A^-_{F\,max} = 0{,}26$.

Verification is performed in the *OrCAD PSpice* environment of the designed oscillator circuit with the element values given in Table 3, using time-domain and Fourier analyses. The following parameters are obtained from the simulation testing: amplitude of the output voltage $U_{om} = 340mV$, frequency of the generated signal $f_{G\,min} = 2{,}9MHz$ and nonlinear distortion coefficient $k_f = 0{,}85\%$.

For the minimal capacitance value of the varicap $C_{V\,min} = 12{,}5pF$ the following values are obtained: $U_{om} = 358mV$, $f_{G\,max} = 10{,}8MHz$ (for $U_c = 8{,}5V$).

For testing of the simulated results they are compared with the measured results of the oscillator realized with the element values corresponding to the simulation variant number 26 (Table 3). The results, obtained from the experimental testing of the LC oscillator, are summarized in Table 4.

Table 4.

№	Control voltage V_C	Output frequency f_G	Output voltage V_{om}
1	0,5V min	3,1MHz	270mV
2	8,5V max	9,09MHz	650mV

The LC oscillator (Fig. 2), realized with CFA AD844A and varicaps BB112, is also designed and tested. Some of the circuit parameters, determined by simulation testing and optimal variant selection, are the following: $L_1 = 7\mu H$ ($w_1 = 50$), $L_2 = 3{,}3\mu H$ ($w_2 = 20$), $M = 1{,}41\mu H$, $k = 0{,}29$, $R_1 = 687\Omega$, $R_2 = 1{,}16k\Omega$, $R_3 = 988\Omega$, $R_4 = 247\Omega$ and $C_1 = 131pF$. The obtained experimental results are given in Table 5.

Table 5.

№	Control voltage V_C	Output frequency f_G	Output voltage V_{om}
1	0,5V min	22MHz	400mV
2	8,5V max	25MHz	400mV

4. CONCLUSIONS

In the present paper a voltage controlled LC oscillator has been proposed, built on the base of CFA with an additional port for control. An oscillator design methodology is developed based on results from theoretical analysis and simulation testing in the OrCAD PSpice environment. Using this methodology, the influence of the circuit elements on the conditions of selfoscillation and the working frequency range are highlighted, which gives the possibility of finding fast an optimal solution. An example is given for the oscillator design according to the proposed methodology using CFA AD844A and varicaps in the resonant circuit BB112.

5. REFERENCES

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