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Simulation of Frequency Properties of Operational Amplifiers in Analog-Digital Signal Processing Devices

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Abstract— **The mathematical models of frequency properties of operational amplifiers (OAs), formed by submicron combined gallium arsenide and silicon technologies, are presented. This approach considerably increases the dynamic range at voltage, frequency and temperature in analog-digital signal processing devices. The paper describes three areas of application of OAs. In the first area, a modernized differential cascade based on bipolar or Schottky field transistors is used, which ensures the symmetry of its characteristics and high speed. The second class of tasks relates to the development of active RC-filters, in which unpacked OA is the active element, formed by submicron gallium arsenide and silicon technologies, and RC-links formed by the original tantalum technology. The simulation of active RC-filters based on gyrators performed on OAs is realised. The use of a gyrator eliminates completely the use of inductive elements. The third type of task represents the simulation of comparators formed on unpacked OAs, which allows their effective use in microcontrollers of analog-to-digital and digital-to-analog converters at digital processing of signals.**

Keywords— operational amplifier, RC-filter, comparator, analog-to-digital converter, tantalum submicron technology.

I. INTRODUCTION

Today, information technologies, which became the basis of large systems, significantly changed the concept of their construction and led to new structure-circuit and technological means of their practical implementation, namely:

1. High intellectualization of subsystems, which is achieved using of local analog-digital hardware and software systems based on analog and digital-to-analog large and very-large integrated circuits.

2. Sub-and nanomicrotronic technology [1-4] as the basis for the development of computer and information technology will be the basis of the development of the elemental base of microcircuits in the coming years. The combination of silicon and gallium arsenide technologies plays a special role in increasing the dynamic and frequency range and the speed of modern information and telecommunication systems.

Complex researches were conducted at the simulation of the frequency properties of differential and OAs in analog-digital signal processing devices in these directions [1]:

1. In modulators/demodulators on the basis of integral multipliers, schematically and topologically formed on differential cascades of OAs.

2. In precise filter circuits, implemented integrally on the basis of tantalum technology and active unpacked OAs.

3. In integral comparators for microanalog-to-digital converters.

II. METHOD OF REALIZING TASK 1

The first task is solved by the schematic, topological and technological realization of the precision differential cascade of OAs on two-gate field or bipolar Schottky transistors with zero bias voltage. This provided a high symmetry of the multiplier circuit, a significant increase in the dynamic range of both the voltage and the frequency (up to 5 GHz) and the temperature range (-65 ÷ +250°C) by forming integral structures with a combined epitaxial gallium arsenide technology on mono-silicon substrates. The proposed circuit design solution allowed construct an original multiplier based on the modernized in such way differential cascade. This multiplier became the basis for the design of microwave modulators/demodulators, manipulators/demanipulators, synthesizers and frequency dividers in the integrated design, which allowed them to be interconnected in different microprocessor and microcontroller circuits [1,2].

Schematic realization of differential cascade on two-gate field or bipolar Schottky transistors is given in Fig. 1.

The mathematical model of the multiplier on the differential cascade will be represented by the following expression:

$$\Delta U_{out} = \frac{I_0 R_L}{2\varphi_t^2}(U_2 - U_1)(V_2 - V_1) = kUV, \qquad (1$$

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where I_0 – current source, R_L – load resistance, φ_t – temperature coefficient, $k = \frac{I_0 R_L}{2\varphi_t^2}$.

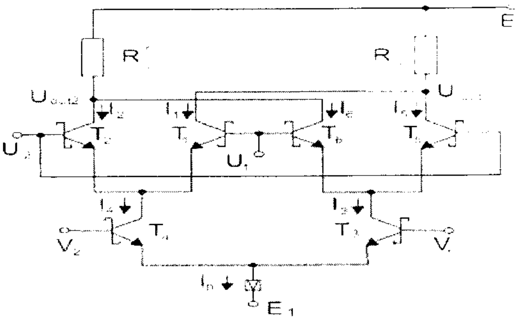

Fig. 1. The structure of the electric circuit of the multiplier on the differential cascade of the Schottky bipolar transistors.

The differential modernized cascade (DC), which has an improved symmetry and dynamic range and is the basis of the opiate operating amplifiers and comparators, is the basis of multiplication, and its circuitry is presented in Fig. We will analyze the electrically circuit of such a multiplier, and build on it modulators/demodulators, manipulators/demanipulators and synthesizers.

The voltage difference $(U_{out1} - U_{out2})$ forms the differential signal U_{out0} - load balances R_L and R_L' is defined by the expression:

$$\Delta U_{out} = U_{out2} - U_{out1} = [(I_2 + I_6) - (I_1 + I_5)] * R_L, \qquad (2)$$

or

$$\Delta U_{out} = [(I_2 - I_1) + (I_6 - I_5)] * R_L \qquad (3)$$

If the differential signal is removed from one shoulder DC, then we obtain:

$$\Delta U_{out} = \frac{\Delta U_{out0}}{2} = \frac{I_0 R_L}{4\varphi_t^2}(U_2 - U_1)(V_2 - V_1) = W \qquad (4)$$

Denoting $k = \frac{I_0 R_L}{4\varphi_t^2}$, we get $W = kUV$ the expression that is performed by the differential multiplier. The coefficient k, which does not depend on the factors U and V, is determined by regime and temperature factors.

The structure of multiplier is given in Fig. 2

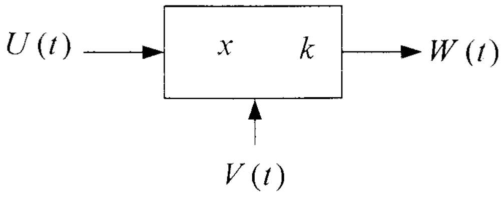

Fig. 2. The structure of multiplier

If $U(t) = U_m \cos\omega t$ is a carrier frequency signal, and $V(t) = V_m(1 + m\cos\Omega t)$ at $m \le 1$ – message signal, then the output of the multiplier on the basis of the differential cascade will be determined by a spectrum of three signals:

$$W(t) = kU_m V_m \cos\omega t + mk\frac{U_m V_m}{2}\cos(\omega + \Omega)t + \\ + mk\frac{U_m V_m}{2}\cos(\omega - \Omega)t, \qquad (5)$$

representing an amplitude modulator.

If the signal $V(t)$ is passed through the amplitude limiter, i.e. $V(t) = V_m \cos\omega t$, and and the signal from the output of the multiplier $W(t)$ to pass through the low pass filter, which holds the second harmonic, then can obtain at the output:

$$U_{out} = U_{out}(t) = \frac{U_m(t)V_m}{2}k\,k_f\,, \qquad (6)$$

where k_f – gain coefficient of low pass filter. As a result, we obtain a low-frequency signal that is proportional to the message $U_m(t)$, which is an amplitude detector.

As we see, on the basis of the integral differential cascade, formed on the basis of the combined gallium arsenide and silicon technologies, not only modulators/demodulators of analog message, but also manipulators/demanipulators of digital message, as well as synthesizers and frequency dividers are formed.

III. METHODS OF REALIZING TASK2

The second type of task was solved by developing active RC-filters based on tantalum technology and active elements of unpacked OAs or Darlington circuits, studying their frequency properties on the basis of the doctrines of Butterworth, Chebyshev, Bessel (research and development work "Circle"). In this case, both silicon and combined gallium arsenide technologies were used to form active elements. The simulation of the frequency properties of active RC-filters was performed by the Matlab software [illegible] using packages: SP – Signal Processing, Comm – Communications, FD – Filter Design. This allowed to realize not only analogue (high- and low-frequency), but also digital (transversal and recursive) filters for ground and onboard radar systems.

A one-band transmission is used in a distant cosmic communication and the structure of its modulator is given in Fig. 3.

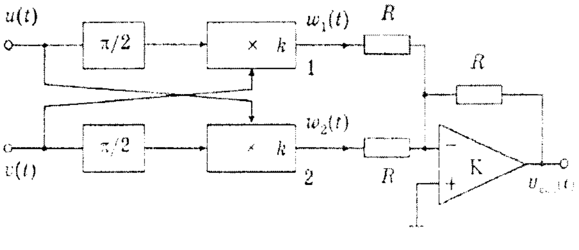

Fig. 3. The structure scheme of a one-band amplitude modulator.

Here at the inputs of the circuit there are sinusoidal signals $U(t) = U_m \cos\omega t$ and $V(t) = V_m \cos\Omega t$. Then passing through the phase shifter and the multipliers form the input of the inverting adder on the operating amplifier signal.

A narrow-band pass active filters based on the gyrators were investigated within the frame of this work. They schematically represent the counter-parallel switching of two OAs: inverting one –A and non-inverting + A, the scheme of which is given in Fig. 4.

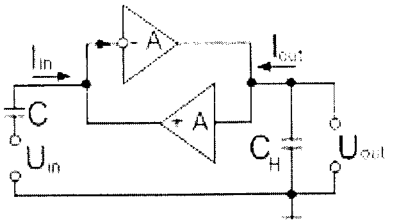

Fig. 4. Electrical circuit of a narrow-band pass active filter based on a gyrator.

Consider the circuitry and technology of such filters forming. Gyrator amplifiers are characterized by high input $R_{in} \to \infty$ and low output $R_{out} \to 0$ resistances. Equation of transfer of a gyrator on the OA basis is determined by the relations:

$$U_{in} = -I_{out} R_g , \; I_{in} = -U_{out} / R_g , \tag{7}$$

where R_g – the resistance of the hydrator as a converter on the OA, which at least expresses its amplification properties.

The resistance of the gyrator can be determined from these equations as:

$$Z_{in} = U_{in} / I_{in} = I_{out} R_g^2 / U_{out} , \tag{8}$$

where $I_{out} / U_{out} = 1 / Z_{load}$.

Then the input resistance of the gyrator will be determined by the ratio:

$$Z_{in} = R_g^2 / Z_{load} , \tag{9}$$

where Z_{load} – load resistance at the output of the gyrator. If the gyrator is loaded on a capacitance C_{load}, then its input resistance will have an induced character:

$$Z_{in} = R_g^2 / Z_c = j \omega \, C_{load} \, R_g^2 = j \omega \, L_{eq} , \tag{10}$$

where $L_{eq} = C_{load} \, R_g^2$.

If the capacitors C and C_{load} are schematically embedded in the input and output of the gyrator, then as a result, can obtain an active filter that is equivalent to the successive LC-circuit (Fig. 5).

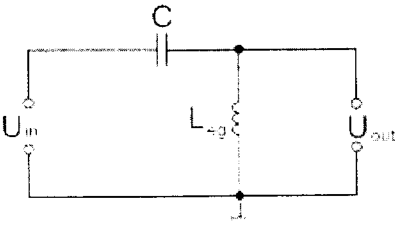

Fig. 5. Equivalent circuit of a narrow-band pass active filter based on a gyrator.

This scheme is already less sensitive to thermo-field changes parameters of the OA and RC-components of the tantalum technology.

Its equivalent scheme as a filter is given in Fig. 6, where $I_{in} = j \omega C R_1 R_3 R_4 / R_2 = j \omega L_{eq}$, $L_{eq} = C R_1 R_3 R_4 / R_2$.

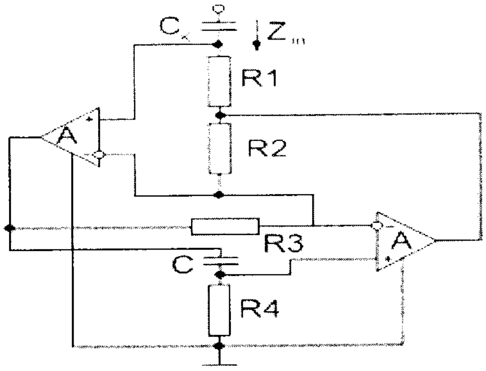

Fig. 6. Improved electrical circuit of a narrow band gyrator filter basec two OAs.

This precision inductance is provided by the develop tantalum technology, which extends the temperature ran of the filters from -65 to +250°C, if the OAs are formed combined gallium arsenide and silicon technologies.

To implement a precision gyrator, it is not necessar use two OAs. There is an opportunity to realise a gyrator one amplifier (Fig. 7).

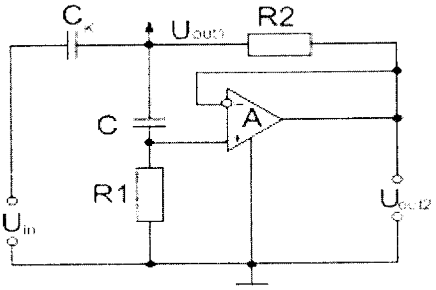

Fig. 7. Electrical circuit of gyrator filter based on one OA.

For this scheme, covered by a moderate feedback, equivalent inductance is determined by the $L_{eq} = R_1 R_2 C$, since the unpacked OA is used in repeater mode with the coefficient $k = 1$. $R_1 = (100 \div 200) R_2$ and the input resistance of $R_{in} > R_2$, than the quality factor of the filter will determined by the expression $Q_{eq} = 0,5 (R_1 / R_2)^{1/2}$ allows the formation of very stable narrow-band filters on-board radar systems, in particular bisquare narrowb filter, due to the above-mentioned technologies.

IV. METHODS OF REALIZING TASK3

Let's consider at the third version of the simulatio frequency propetries of the OA based on the compara which are the main part of devices of the ADC-DAC digital signal processing.

Since large volumes of information are being digitized at present, ADC are used to convert an analog signal to a digital form but with a DAC reverse combination.

Modern integral voltage comparators (IVCs) are comparision devices in digital signal processing systems, which are intended for comparison two input voltages. Depending on the voltage difference sign at the IVC inputs, the potential is set at output, which corresponding to either the logical "1" or the logical "0". In order to combine IVCs with digital integrated circuits, the specified absolute values of output potential should be equal to the ones corresponding to the logical levels of these circuits.

The main parameters of the comparators are:

- sensitivity, defined error with which the comparator can distinguish analyzed and reference signals;

- speed, which is characterized by the delay of the operation and the time of the increase of the input signal;

- loading capacity, the measure of which is determined by the number of simultaneously connected digital integrated circuits inputs that do not violate the operation of the comparator.

The block diagram of IVC is the same as for integral OA and contains at the input a differential cascade that performs the comparison function. An intermediate amplifier with a high gain is usually placed after the input differential cascade in order to increase the sensitivity of IVC. It provides the formation of high voltage amplitude variations at a small difference of input voltage. The special difference between the IVC and the integral OA is the circuitry of the output cascades. The output cascade in IVC works in key mode, generating potential levels that correspond to the logical "0" and the logical "1".

Modern IVCs belong to a class of analog-digital elements (devices) and there are the following types: universal, precision based on high-speed integrated circuits. They are used in signal processing systems.

The accuracy of the input voltages comparison is determined by folowing parameters of the IVCs:

– input bias voltage $U_{in\ bias}$, which is an analog of $U_{in\ offset}$ for integral OA;

– input offset current $I_{in\ offset}$;

– input bias current $I_{in\ bias}$, which determines the asymmetry of the cascade;

– power source instability factor k_{inst}.

The simulation of the frequency properties of IVCs of 521CA4 series was studied in this paper. These comparators belongs to the class of precision high-speed devices implemented on the basis of the combined technology of GaAs epitaxial layers on mono-silicon substrates. Such technology provides:

– high precision of comparison (< 10 μV);

– low power consumption (< 1 W);

– high speed (delay time < 30 ns);

– high sensitivity coefficient (k_y > 25 V/mV);

– large frequency range (> 50 GHz).

Such parameters are achieved using proper element base – Schottky bipolar and Schottky field-effect transistors at inputs of differential cascades (two-gate transistors). Its circuitry is given in Fig. 8

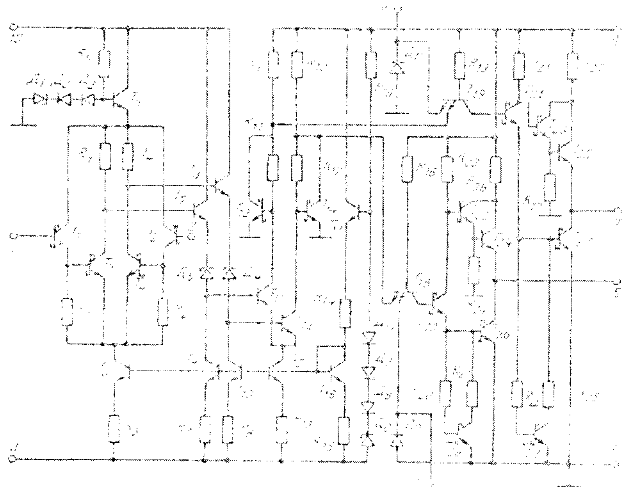

Fig. 8. Integral voltage comparator 521CA4

In this figure, an integral, high-performance voltage comparator 521CA4 is provided, which has the following outputs: 1 - analog input 1; 2- analog input 2; 3 - supply voltage ($-U_1$); 4 - logical input 2 (strobe2); 5- logical output 2; 6 - general; 7 - logical output 1 (strobe1); 8 - logical input 1 (strobe1); 9 - supply voltage (U_2); 10 - supply voltage (U_3).

Such IVCs provide the formation of original modulators manipulators on ADC-DAC multipliers.

V. CONCLUSION

1. The original technology of forming of precision differential operational amplifiers and comparators with the use of submicron combined gallium arsenide technology is developed.

2. The simulation of the frequency properties of operational amplifiers is performed, which showed their high precision, speed and noise immunity.

3. The original schemes of the gyrators on unpacked operational amplifiers, which exclude the use of inductive elements, are developed.

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