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NOVEL RADIO SYSTEMS AND ELEMENTS

Measurement of the Stability Margin of an Immittance Logic Gate

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Abstract—A setup for the measurement of the stability margin of an immittance AND gate is proposed. The feasibility of the measurement method, which is applicable regardless of whether the gate is stable or potentially unstable, is validated.

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INTRODUCTION

Immittance logic gates (ILGs) utilize a new information basis (immittance logic [1]), thus offering opportunities for further progress in the RF information engineering (including the design of special-purpose equipment).

The ILG logic level in the immittance logic is characterized by just its nature or sign rather than a certain value of the immittance parameter.

The use of immittance logic in the design of gates allows one to process radio data directly at the carrier frequency [2–5]. The ILGs provide an opportunity to:

(i) enhance the noise immunity of radio data processing and transmission systems;

(ii) reduce the power consumption by using the same voltage levels for logic 0 and 1 that are significantly lower than those used for discrete data representation by pulse level signals;

(iii) avoid one of the disadvantages of discrete data representation by pulse level signals: the need in direct transmission of signals with low-frequency components in their frequency spectra;

(iv) construct the information-processing equipment with high level of access security;

(v) simplify the design of data acquisition and processing equipment via application of many-valuedness and by reducing the number of interconnections.

In contrast to the majority of engineering solutions applied in the design of RF logic gates, which utilize nonlinear properties of semiconductor devices [2, 6–8], the ILGs are operated in the quasilinear mode. This ensures high noise immunity and operating speed of these gates (see [9]). Owing to the influence of on-chip positive feedback and the fact that the working point of transistors used in the ILGs is in the active region, such ILGs may be potentially unstable. This raises the problem of analytical estimation of this instability at the ILG design stage in order to determine application conditions for these logic gates or ensure stable operation. This estimate allows one to determine values of the compensating admittance required for absolute ILG stability and thus design absolutely stable ILGs.

1. JUSTIFICATION OF THE METHOD

The aim of this study is to develop a method for measuring the ILG stability margin and determine the conditions under which their stable operation is established. The following is needed in order to achieve this goal:

(i) analytical justification of the measurement method;

(ii) analytical estimation of the ILG stability condition;

(iii) implementation of the measurement method and its numerical validation.

An immittance logic gate is a multiparameter generalized immittance converter (GIC_N) [10]. The immittances to be converted (W_i) characterize input logic variables, and converted immittance W_{out} characterizes the output logic variable:

$$W_{\text{out}} = T(W_1, W_2, \ldots, W_n),$$

where $n = N - 1$, T is the immittance conversion coefficient, and N is the number of terminals of a device used to implement GIC_N.

Since two-input logic gates are most commonly used, the ILG presented in Fig. 1 is used in the analytical justification of the measurement method.

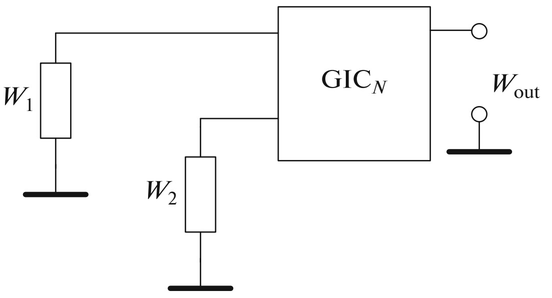

Fig. 1. Circuit of the immittance logic gate.

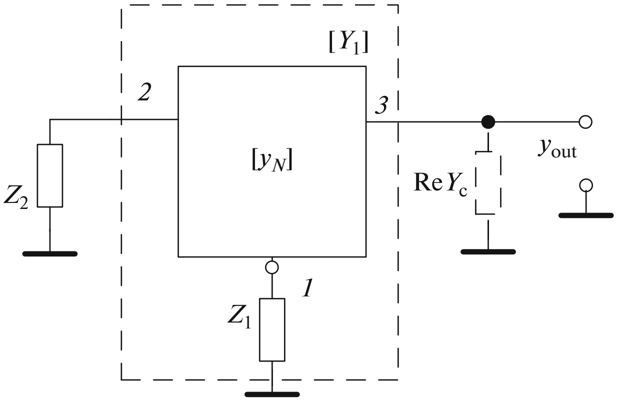

Fig. 2. First and second (*1* and *2*) immittance conversion channels and (*3*) the output channel.

Each immittance conversion channel is regarded as a four-terminal device with immittances W_1 and W_2 connected at its input. The output immittance of this device is $W_{\text{out}\,1} = T_1(W_1)$ for $W_2 = \text{const}$ and $W_{\text{out}\,2} = T_2(W_2)$ for $W_1 = \text{const}$.

With these assumptions taken into account, each immittance conversion channel may be represented as a four-terminal device characterized by admittance matrix $[y_1]$ with impedance Z_2 or Z_1 connected to its common terminal (Fig. 2).

For the first immittance conversion channel, the admittance matrix of the formed four-terminal device with impedance Z_1 factored in takes the form [10]

$$[Y_1] = \begin{bmatrix} Y_{11}^{(1)} & Y_{12}^{(1)} \\ Y_{21}^{(1)} & Y_{22}^{(1)} \end{bmatrix} = \frac{1}{1+Z_1\sum y^{(1)}} \times \begin{bmatrix} y_{22}^{(1)}+Z_1\Delta y^{(1)} & y_{23}^{(1)}-Z_1\Delta y^{(1)} \\ y_{32}^{(1)}-Z_1\Delta y^{(1)} & y_{33}^{(1)}+Z_1\Delta y^{(1)} \end{bmatrix}, \qquad (1)$$

where $y_{22}^{(1)}, y_{23}^{(1)}, y_{32}^{(1)}$ and $y_{33}^{(1)}$ are elements of the indefinite three-terminal device matrix $[y_1]$, $\sum y^{(1)} = y_{22}^{(1)} + y_{23}^{(1)} + y_{32}^{(1)} + y_{33}^{(1)}$, and $\Delta y^{(1)} = y_{22}^{(1)}y_{33}^{(1)} - y_{23}^{(1)}y_{32}^{(1)}$.

We use the internal invariant stability coefficient of the linear four-terminal device [11] to estimate the ILG stability margin. This coefficient for the impedance Z_2 conversion channel is written as

$$K_{\text{st int}}^{(1)} = \frac{2\,\mathrm{Re}(Y_{11}^{(1)})\,\mathrm{Re}(Y_{22}^{(1)}) - \mathrm{Re}(Y_{12}^{(1)}Y_{21}^{(1)})}{\left|Y_{12}^{(1)}Y_{21}^{(1)}\right|}. \qquad (2)$$

It follows from the analysis of (1) and (2) that $K_{\text{st int}}^{(1)}$ depends only on the converted impedance Z_1 and $y^{(1)}$, which are the parameters of the four-terminal device. It is formed by the used three-terminal device with impedance Z_1 connected to the first terminal.

Performing similar analysis for the channel converting impedance Z_2 into output admittance Y_{out}, we find the internal invariant stability coefficient for this channel:

$$K_{\text{st int}}^{(2)} = \frac{2\,\mathrm{Re}(Y_{11}^{(2)})\,\mathrm{Re}(Y_{22}^{(2)}) - \mathrm{Re}(Y_{12}^{(2)}Y_{21}^{(2)})}{\left|Y_{12}^{(2)}Y_{21}^{(2)}\right|}, \qquad (3)$$

where $Y_{11}^{(2)}, Y_{12}^{(2)}, Y_{21}^{(2)}$ and $Y_{22}^{(2)}$ are elements of admittance matrix $[Y_2]$ of the a four-terminal device formed by the used three-terminal device with impedance Z_2 in its common terminal.

Thus, in order to determine $K_{\text{st int}}^{(1)}$ and $K_{\text{st int}}^{(2)}$, one should calculate or measure four parameters of the indefinite admittance matrix of the three-terminal device and set or measure the values of converted impedances Z_1 and Z_2.

2. ESTIMATION OF THE ILG STABILITY CONDITION

It is known that the invariant stability coefficient of any quasi-linear four-terminal device falls within the range $-1 \le K_{\text{st int}} < \infty$ if the $\mathrm{Re}\,Y_{11} > 0$ and $\mathrm{Re}\,Y_{22} > 0$ condition is satisfied [11]. The value $K_{\text{st int}} = 1$ corresponds to the stability boundary. Four-terminal devices based on modern transistors tend to be potentially unstable with $K_{\text{st int}} < 1$. Their stability ($K_{\text{st int}} > 1$) is generally established by adjusting the impedance value in the common terminal (in the case under consideration, Z_1 or Z_2). However, this is not applicable to the ILGs since Z_1 and Z_2 are input information parameters. Their qualitative state (inductive, capacitive, or resistive immittance) is fixed, while the quantitative parameter is undefined (in accordance with the concept of "indeterminate immittance" [12]). In the general case, boundary values of these immittances are determinate, but they cannot be used to stabilize ILGs in the entire range of variation of input parameters Z_1 and Z_2.

One way to solve this problem is to connect compensating active admittance $\mathrm{Re}Y_{\mathrm{c}}$ to the ILG output (Fig. 2). The stability margin is then expanded to

$$K_{\mathrm{st}} = \frac{2\,\mathrm{Re}\,Y_{11}\,\mathrm{Re}(Y_{22}+Y_{\mathrm{c}}) - \mathrm{Re}(Y_{12}Y_{21})}{\left|Y_{12}^{(1)}Y_{21}^{(1)}\right|} > 1. \tag{4}$$

Solving inequality (4), we obtain the following result:

$$\mathrm{Re}\,Y_{\mathrm{c}} > \frac{\left|Y_{12}^{(1)}Y_{21}^{(1)}\right| + \mathrm{Re}(Y_{12}Y_{21})}{2\,\mathrm{Re}\,Y_{11}} - \mathrm{Re}\,Y_{22}. \tag{5}$$

Thus, if parameters of the immittance matrix of each immittance conversion channel and the range of variation of converted impedances Z_1 and Z_2 are known, it is sufficient to calculate compensating admittances $Y_{\mathrm{c}1}$ and $Y_{\mathrm{c}2}$ for each channel. Choosing the larger value, we obtain the condition of absolute ILG stability.

3. IMPLEMENTATION OF THE MEASUREMENT METHOD AND ITS VALIDATION

The major problem of implementation consists in the large error in the measured values of parameters of the admittance matrix of the four-terminal device in the microwave range. If a common measurement method with the short-circuit mode is used, the error exceeds 20% at a frequency of 1 GHz [13].

Measurement of *S*-parameters of the scattering matrix with subsequent conversion into *Y*-parameters of the admittance matrix also does not solve the mentioned problem. This fact may be attributed to the potential instability of active four-terminal devices and large error of measurement of complex values of $\dot{S}_{12}$ and $\dot{S}_{21}$ [14].

In view of the aforesaid, it seems reasonable to switch from *y*-parameters of the admittance matrix of the three-terminal device to other methods measuring the invariant stability coefficient. In order to accomplish this, we use (3) and (4) to obtain the following:

$$K_{\mathrm{st}} = K_{\mathrm{st\,int}} + \frac{2\,\mathrm{Re}\,Y_{11}\,\mathrm{Re}\,Y_{\mathrm{c}}}{\left|Y_{12}^{(1)}Y_{21}^{(1)}\right|}. \tag{6}$$

It is known [15] that the minimum possible output admittance of a four-terminal device is

$$\mathrm{Re}(Y_{\mathrm{out}})_{\mathrm{min}} = (1 - K_{\mathrm{st\,int}}) + \frac{\left|Y_{12}Y_{21}\right|}{2\,\mathrm{Re}\,Y_{11}}. \tag{7}$$

Solving (6) and (7) together, we find $\mathrm{Re}(Y_{\mathrm{out}})_{\mathrm{min}_i}$ for conversion channel *i*:

$$\mathrm{Re}(Y_{\mathrm{out}})_{\mathrm{min}_i} = \frac{(1 - K_{\mathrm{st\,int}})}{(K_{\mathrm{st}} - K_{\mathrm{st\,int}})}\mathrm{Re}\,Y_{\mathrm{c}}. \tag{8}$$

It follows from (8) that, if the values of $K_{\mathrm{st\,int}}$ and $K_{\mathrm{st}} > 1$ are known and $\mathrm{Re}\,Y_{\mathrm{c}_i}$ is set, one may find the minimum possible real component of the output ILG immittance for each conversion channel regardless of the values of Z_1 and Z_2.

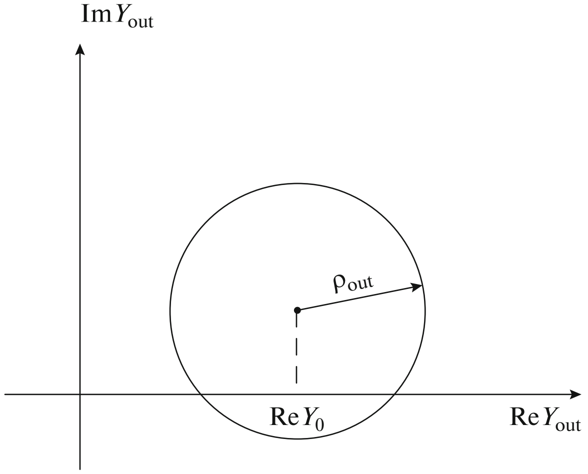

Fig. 3. Measurement of the parameters of the immittance circle.

If $\mathrm{Re}(Y_{\mathrm{out}})_{\mathrm{min}_i} > 0$ for each channel, the ILG is stable at any values of Z_1 and Z_2, and additional compensation is not required ($\mathrm{Re}(Y_{\mathrm{c}}) = 0$).

If $\mathrm{Re}(Y_{\mathrm{out}})_{\mathrm{min}_i} < 0$ for channel *i*, stability of the ILG is established by inserting a compensating resistor with the following real admittance component at its output:

$$\mathrm{Re}\,Y_{\mathrm{c}} > \left|\mathrm{Re}(Y_{\mathrm{out}})_{\mathrm{min}_i}\right|. \tag{9}$$

The ILG stability margin for each channel of conversion of impedance Z is then given by

$$K_{\mathrm{st}\,0} = K_{\mathrm{st\,int}} + \frac{(K_{\mathrm{st\,int}} - 1)\,\mathrm{Re}\,Y_{\mathrm{c}}}{\mathrm{Re}(Y_{\mathrm{out}})_{\mathrm{min}}}. \tag{10}$$

Several methods may be used to determine the invariant stability coefficient of a four-terminal device:

(i) calculation of $K_{\mathrm{st\,int}}$ by formula (2) with the use of *Y*-parameters of the admittance matrix;

(ii) measurement by the Shwarts method [16];

(iii) measurement of parameters of the immittance circle [17] and calculation of the stability coefficient in accordance with the following formula:

$$K_{\mathrm{st\,int}} = \mathrm{Re}Y_0/\rho_{\mathrm{out}}, \tag{11}$$

where $\mathrm{Re}\,Y_0$ and ρ_{out} are the coordinate of the center and the radius of the immittance circle (Fig. 3).

It was already noted that the first method is inaccurate in the microwave range, which is attributed to the large error of measurement of *Y*-parameters of the admittance matrix.

The Shwarts method is applicable only to stable four-terminal devices ($K_{\mathrm{st\,int}} > 1$), and the studied ILGs may be potentially unstable at the design stage.

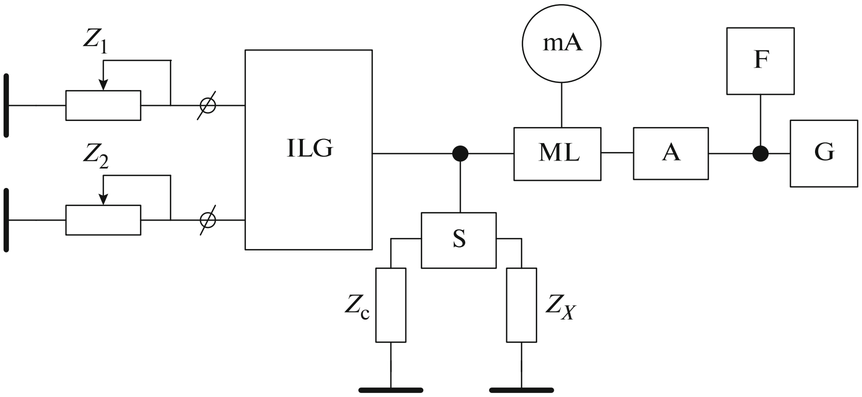

Fig. 4. Experimental setup implementing the "floating immittance" method: ILG is the immittance logic gate, ML is the measurement line, S is the switch, G is the generator, F is the frequency meter, A is the attenuator, and mA is the milliamperemeter.

The third method of the "floating immittance" is the simplest one and is suitable for measuring $K_{\text{st int}}$ in the range $-1 \le K_{\text{st int}} < \infty$. The experimental setup shown in Fig. 4 implements this method. The setup allows one to measure $K_{\text{st int}}$ and K_{st} for each ILG channel and choose the appropriate compensating immittance $\text{Re}Y_c$, which ensures the ILG stability in the entire range of variation of information parameters Z_1 and Z_2.

The measurement algorithm is as follows.

Step 1. The measuring line is calibrated in accordance with the common procedure.

Step 2. The output ILG admittance values are measured without connection of Z_c and Z_X(the known active resistance expressed as the impedance) at three or more arbitrary values $\text{Re}\,Z_1 \gg \text{Im}\,Z_1$ and limiting value Z_2. The values of $K^{(1)}_{\text{st int}1}$ of the first ILG conversion channel are calculated by formula (2).

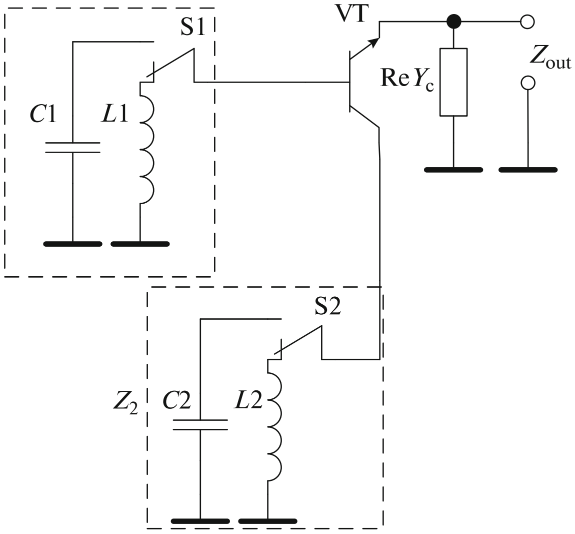

Fig. 5. Microwave circuit of the immittance *LC* AND gate.

Step 3. Switch S is used to connect active resistance Z_X with sufficiently high conductivity $\text{Re}\,Y_X$, which ensures that $K^{(1)}_{\text{st}} > 1$, to the ILG output. Operations similar to those described in Section 1 are performed.

Step 4. Parameter $\text{Re}(Y^{(1)}_{\text{out}})_{\min}$ is calculated using (8) on the basis of the results of measurements of parameters $K^{(1)}_{\text{st int}}$ and $K^{(1)}_{\text{st}}$ and the known $\text{Re}\,Y_X = \text{Re}\,Y_c$.

Step 5. Similar measurements are performed for the second channel and $K^{(2)}_{\text{st int}}$, $K^{(2)}_{\text{st}}$, and $\text{Re}(Y^{(2)}_{\text{out}})_{\min}$ are determined.

Step 6. If $\text{Re}(Y^{(1)}_{\text{out}})_{\min} > 0$ and $\text{Re}(Y^{(2)}_{\text{out}})_{\min} > 0$, the designed ILG is stable.

If one of values of $\text{Re}(Y_{\text{out}})_{\min}$ calculated at the fourth and the fifth steps is negative, the ILG is potentially unstable. Therefore, compensating admittance $\text{Re}Y_c$ should be inserted at its output. This admittance is calculated using (9) with subsequent evaluation of the ILG stability margin by formula (10).

The method was validated with an immittance *LC* logic gate via computer modeling in Microwave Office as well as experimentally. The microwave circuit of the experimental sample (without supply circuits) is shown in Fig. 5. This sample uses inductive resistance $Z_L = j\omega L$, which corresponds to logic 1, and capacitive resistance $Z_C = 1/j\omega C$ (logic 0) as input information parameters. Logic 0 and 1 are represented by the considered ILG in accordance with Table 1.

It follows from the analysis of this circuit that transistor VT is in the common-collector configuration (reactive impedance Z_2 is connected to the common terminal) with respect to the first input, the admittance of which is set by the position of switch S1, and in the inverted common-base configuration (reactive impedance Z_1 is connected to the common terminal) with respect to the second input, the admittance state of which is set by the position of switch S2.

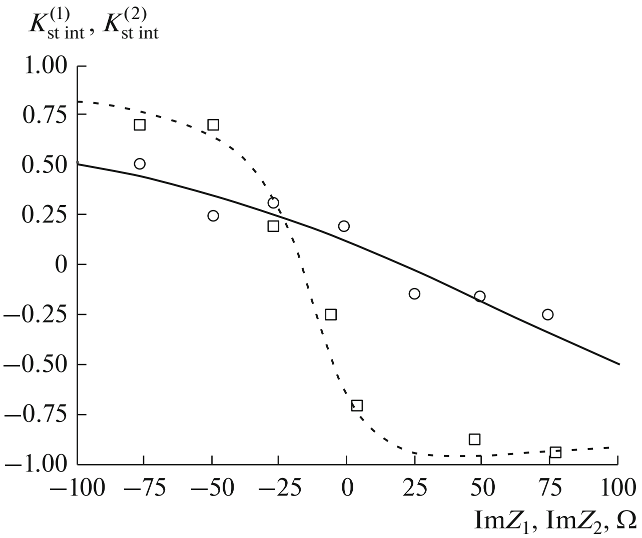

Fig. 6. Dependences of the invariant ILG stability coefficients on the values of input impedances $\text{Im}\,Z_1$ and $\text{Im}\,Z_2$ in the potentially unstable mode. Circles and squares represent the experimental data; solid and dashed curves, the results of calculations obtained for common-collector and common-base transistors.

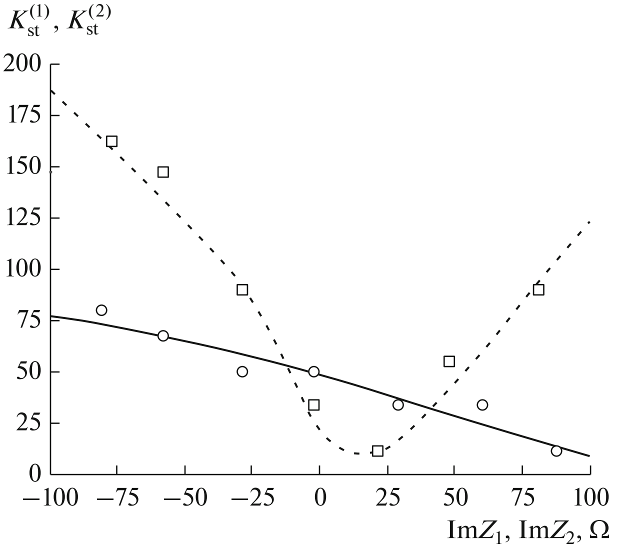

Fig. 7. Dependences of the invariant ILG stability coefficients on the values of input impedances $\text{Im}\,Z_1$ and $\text{Im}\,Z_2$ in the stable mode. Circles and squares represent the experimental data; solid and dashed curves, the results of calculations obtained for common-collector and common-base transistors.

Formulas (1) and (2) were used to calculate and measure internal invariant stability coefficients $K^{(1)}_{\text{st int}}$ and $K^{(2)}_{\text{st int}}$, which characterize the stability of the considered admittance conversion channels, for each of these circuits (Fig. 6). This analysis was performed for a KT3115 transistor at the following parameters: frequency $f = 1$ GHz, collector–emitter voltage $U_{\text{ec}} = 5$ V, and collector current $I_{\text{c}} = 5$ mA.

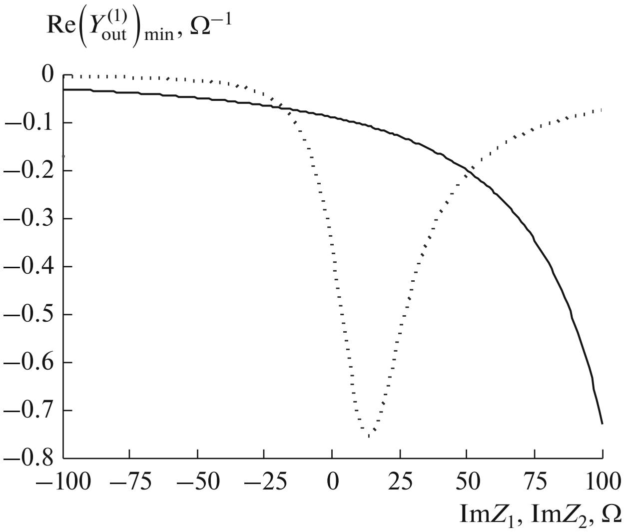

Fig. 8. Calculated dependences of the minimum possible negative active output ILG impedance for each conversion channel. Solid and dashed curves are the results of calculations obtained for common-collector and common-base transistors.

It can be seen that the considered circuits are potentially unstable ($K^{(1)}_{\text{st int}} < 1$ and $K^{(2)}_{\text{yst int вн}} < 1$) in the entire range of variation of input impedances $\text{Im}\,Z_1$ and $\text{Im}\,Z_2$.

Figure 7, which is based on (4), shows that connection of a sufficiently large compensating active admittance $\text{Re}Y_{\text{c}1} = 5\ \Omega^{-1}$ to the ILG output ensures ILG stability in each admittance conversion channel $K^{(1)}_{\text{st}} > 1$ and $K^{(2)}_{\text{st}} > 1$).

In addition to stabilizing the ILG, the compensating admittance shunts the output circuit. In the case of their cascade use, this requires application of isolators or transmission-line passive transformers. In view of this fact, it seems reasonable to use the minimum possible value of $\text{Re}(Y_{\text{c}})_{\text{min}}$. This value was determined using (8) by calculating the minimum possible negative active output admittance of the ILG $\text{Re}(Y_{\text{out}})_{\text{min}}$ for each admittance conversion channel (Fig. 8).

Table 1. Truth table of an immittance *LC* AND gate

Input 1	Input 2	Output
Z_1	Z_2	Z_{out}
$0 - (Z_C)$	$0 - (Z_C)$	$0 - (Z_C)$
$0 - (Z_C)$	$1 - (Z_L)$	$0 - (Z_C)$
$1 - (Z_L)$	$0 - (Z_C)$	$0 - (Z_C)$
$1 - (Z_L)$	$1 - (Z_L)$	$1 - (Z_L)$

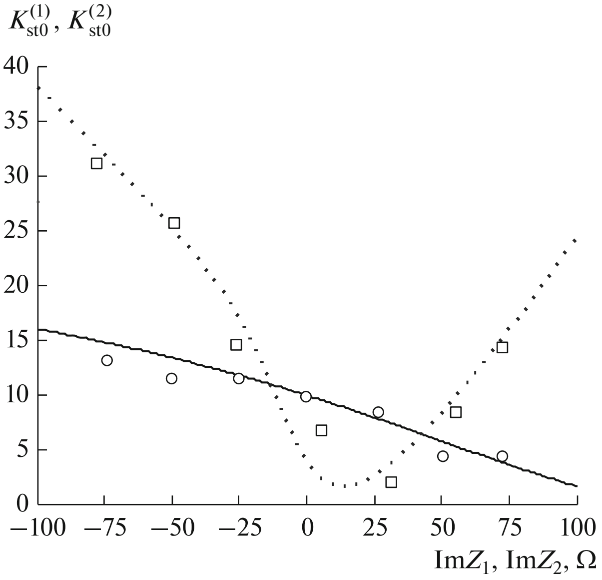

Fig. 9. Dependences of the invariant ILG stability coefficients on the imaginary components of converted immittances in the compensation mode. Circles and squares represent the experimental data; solid and dashed curves, the results of calculations obtained for common-collector and common-base transistors.

Admittance $\mathrm{Re}(Y_{\mathrm{out}})_{\min}$ is higher in the first immittance conversion channel and assumes a value of $-0.75\ \Omega^{-1}$. Admittance $\mathrm{Re}Y_{\mathrm{c0}} = 1\ \Omega^{-1}$ was chosen so as to compensate it.

The corresponding results of calculations and experimental measurements of the stability coefficient in each admittance conversion channel (see Fig. 9) demonstrate that the considered ILG with the optimum compensating admittance is stable ($K_{\mathrm{st0}} > 3$) in the range of variation of input impedances.

CONCLUSIONS

(1) A method for measuring the invariant ILG stability coefficient has been proposed. This method is based on the concept of an immiittance conversion channel and allows one to evaluate the ILG stability margin.

(2) Analytical expressions for the compensating admittance, which ensures ILG stability in the entire range of variation of converted impedances Z_1 and Z_2, have been obtained.

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