Y. S. Tkachuk; S. Y. Fursa, Cand. Sc. (Eng.), Assist. Prof.

MATHEMATICAL MODEL OF THE MULTIPARAMETER GENERALIZED N-STAGE IMMITANCE CONVERTER

The paper develops a mathematical model of the N-stage multiparameter generalized immitance converter, formed by a combination of tripoles. Validation of the model for adequacy has shown its correctness and expediency of its application for designing various types of information devices formed by cascade connection of tripoles.

Key words: *field-effect transistor, tripole, generalized immitance converter, multi-electrode unipolar semiconductor structure.*

Introduction

Fast development of diagnostic and control systems and of their components, determined by growing demand for them in different fields, has led to the necessity of finding new engineering solutions of their structure. One of the ways to solve this problem is application of non-inductive circuits [1]. In order to improve characteristics of such circuits, active devices, operation of which is based on amplifying properties of the active element (most often it is a transistor), are widely used. An alternative way of building such circuits is application of ideal or close-to-ideal devices – generalized immitance converters (converters of resistance or conduction). According to the definition, a generalized immitance converter (GIC) is a quadripole, the input (output) immitance of which depends on immitance of the load (the generator). If the converted immitance of GIC is a function of several converted immitances, such converter is called a multiparameter GIC_N. In fact, multiparameter GIC are multifunctional components, which enables development of various analogue and digital electronic devices on their basis, e.g. switches, active filters, etc. For designing information devices, based on multiparameter GIC, mathematical models, taking into account their special features, are required.

Aim and tasks of the research

Multiparameter GIC_N have shown their advantages for building radiofrequency sensors [3]. However, the problems of their sensitivity, frequency properties, and intensity of the information parameter effect on the primary measuring transducers have not been adequately investigated or investigated only partially [4]. Therefore, the paper aims at the analytical description of GIC_N basic parameters, determination of their converted conduction dependence on the number of stages N as well as on the parameters of each separate stage. To achieve the aim, the following problems should be solved:

- to develop of a mathematical model of the multiparameter GIC_N, based on N-stage connection of three-electrode unipolar semiconductor structures, by means of determining parameters of indefinite immitance matrix of such GIC_N;
- to evaluate adequacy of the developed mathematical model of multiparameter N-stage GIC_N.

Substantiation of the necessity to develop a mathematical model of multiparameter GIC_N

A definite system of parameters is effective for description of multiparaneter GIC_N [5]. Its significant advantage is connection with the parameters of immitance W matrix of a dependent quadripole used as GIC_N (1), which enables simulation of processes of the elements under study in such modern software packages as AWR Design Environment, that work with immitance and wave matrix parameters.

$$[W]=\begin{bmatrix} W_{11} & W_{12} \\ W_{21} & W_{22} \end{bmatrix}, \tag{1}$$

where W_{11}, W_{12}, W_{21}, W_{22} – immitance matrix parameters.

Any quasilinear N-pole is also uniquely described by indefinite immitance matrix:

$$[W_N]=\begin{bmatrix} W_{11} & W_{12} & ... & W_{1N} \\ W_{21} & W_{22} & ... & W_{2N} \\ ... & ... & ... & ... \\ W_{N1} & W_{N2} & ... & W_{N} \end{bmatrix}. \tag{2}$$

The above system of parameters satisfies the requirements of completeness and objectivity:

1. The converted immitance W_{output} (W_{input}) is the function of several parameters and depends on a number of values of the converted immitances:

– for direct conversion $W_{input.j} = T_{ij}(W_{Hi})$;

– for reverse conversion $W_{output.j} = T_{ij}(W_{Li})$.

2. Immitance conversion coefficient – T is the function of converted immitances and indefinite quadripole immitance matrix:

$$T = F(W_L, W_G, [W]). \tag{3}$$

3. Invariant stability coefficient K_s, on one hand, characterizes GIC_N stability margin and on the other hand, makes it possible to evaluate GIC_N capabilities, when negative resistance is realized at its terminals, which provides wide functional capabilities for creation of various new information devices. This coefficient enables quantitative estimation of potential instability and for an unloaded quadripole is described by the expression:

$$K_s = \left(2\,ReW_{11}\,ReW_{22} - Re(W_{12}W_{21})\right)/\left|W_{12}W_{21}\right|.$$

If quadripole is loaded, invariant stability coefficient must, along with the parameters of indefinite quadripole matrix, also take into account resistance of the load:

$$K_{s.in} = \left(2\,Re(W_{11}+W_G)\cdot ReW_{22} - Re(W_{12}\cdot W_{21})\right)/\left|W_{12}\cdot W_{21}\right|. \tag{4}$$

4. Frequency, which corresponds to GIC_N potential instability margin and is a boundary frequency f_G ($K_s = 1$).

5. One of the requirements to generalized immitance converters (GIC_N) is stability of the conversion coefficient. Instability of this coefficient is usually characterized by sensitivity to the change of GIC_N parameters $S^T_{\alpha_i}$, which was called the "quality" of GIC_N [6]. The lower the sensitivity of GIC_N, the higher its quality is:

$$S^T_{\alpha_i} = \frac{\partial T}{\partial \alpha_i} \div \frac{\partial \alpha_i}{T}; \tag{5}$$

where α_i – physical parameter of GIC_N.

6. GIC_N can both amplify a signal and cause its fading. This GIC_N property is quantitatively

characterized by maximally attainable quadripole power transfer coefficient at its stability margin – K_{MS}:

$$K_{ms}(K_s = 1) = \left|\frac{W_{21}}{W_{12}}\right|. \tag{6}$$

7. If GIC_N is potentially instable ($K_{s.in}$<1), real immitance Re$W^{(-)}_{max}$ can be realized at its terminals, the presence of which is the evidence of extended functional capabilities of GIC_N. Maximally attainable negative real immitance

– for direct conversion

$$Re\,W^{(-)}_{input.max} = W_{12}W_{21}\left|\frac{(1-K_{s.in})}{2\,Re\,W_{22}}\right|; \tag{7}$$

– for reverse conversion

$$Re\,W^{(-)}_{output.max} = W_{12}W_{21}\left|\frac{(1-K_{s.in})}{2\,Re\,W_{11}}\right|. \tag{8}$$

8. The value of this immitance could be different at the input Re$W^{(-)}_{input.\,max}$ and output $W^{(-)}_{output.max}$ terminals of GIC_N, which is the evidence of its nonreciprocal properties estimated by non-reciprocity coefficient K_{NR}.

$$K_L = \frac{Re\,W^{(-)}_{input.max}}{Re\,W^{(-)}_{output.max}}. \tag{9}$$

– for stable GIC_N K_{NR} (Ks >1) = $|W_{21}/W_{12}|^2 = K^2_{ms}$;

– for potentially unstable GIC_N K_{NR} (K_s <1) = $\mathrm{Re}W_{22}/\mathrm{Re}W_{11}$.

9. Re$W^{(-)}_{max}$ changes in frequency range. Frequency, which corresponds to the maximal value of Re$W^{(-)}_{max}$ for constant value of the converted immitance, is called optimal conversion frequency f_{opt}.

$$f_{opt} = \left(\partial\,Re\,W^{(-)}_{max}\big/\partial f = 0\right). \tag{10}$$

10. Immitance circuit parameters are as follows:

radius $\rho_{output} = |W_{12}\cdot W_{21}|/2\cdot Re(W_{11}+W_\Gamma)$,

active component of the immitance circuit centre coordinate $Re\,W_{output.0} = Re\,W_{22} - Re(W_{12}\cdot W_{21})/2\,Re(W_{11}+W_\Gamma)$.

Mathematical formalization of the component elements of matrix W_N will make it possible to determine and to estimate quantitatively the parameters of expressions (3) – (10).

Development of the mathematical model of multiparameter GIC_N formed by a combination of tripoles

A tripole-based GIC_N is the simplest multiparametric GIC_N, that could be a basic member of more complex GIC_N. For development of the mathematical model of a sensor, based on multistage multiparameter GIC_N connection, the following boundary conditions are adopted:

- GIC_N is realized on the basis of quasilinear active tripoles [7, 8] described by y-matrix of conduction;

- each stage of multiparameter GIC_N is a two-parameter grounding of GIC_N;
- two-pole devices, that realize the converted immitances W_{Gi},are passive;
- input W_{11} and output W_{22} immitances of each stage of the multiparameter GIC_N must have values above zero while transfer immitances W_{12} and $W_{21} \neq 0$;
- N-stage connection of such multiparameter GIC_N could be represented in the form of a generalized structural diagram (Fig. 1), which does not depend on the physical mechanism of operation of active devices .

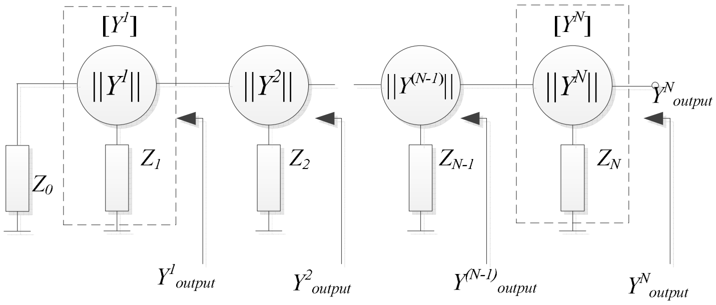


Fig. 1. N-stage connection of multiparameter GIC_N

For generalized immitance converters mathematical model development mechanism is the same, irrespective of the number of stages. To ease understanding, we will develop mathematical model for a two-stage multiparameter GIC_N. Structural diagram of such multiparameter GIC_N is presented in Fig. 2.

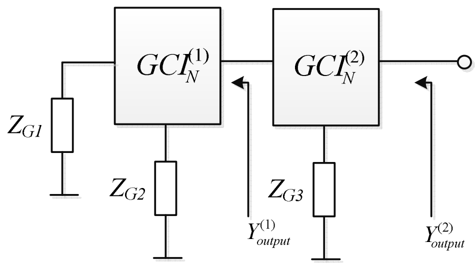


Fig. 2. Structural diagram of two-stage three-parameter GIC_N

Each stage of such structure could be described by $[Y_i]$ matrix, that is dependent on the parameters of $[y_i]$-matrix of the active quadripole and converted impedances $Z_{(i-1)}$ and Z_i, using the following relations [5]:

$$Y_{11}^i = \left(y_{11}^i + Z_i \Delta y_i\right) \big/ K_i \,; \quad Y_{12}^i = \left(y_{12}^i - Z_i \Delta y_i\right) \big/ K_i \,;$$

$$Y_{21}^i = \left(y_{21}^i - Z_i \Delta y_i\right) \big/ K_i \,; \quad Y_{22}^i = \left(y_{22}^i + Z_i \Delta y_i\right) \big/ K_i \,, \qquad (11)$$

where $K_i = 1 + Z_i \sum y_i ; \sum y_i = y_{11}^i + y_{12}^i + y_{21}^i + y_{22}^i ; \Delta y_i = y_{11}^i \cdot y_{22}^i - y_{21}^i \cdot y_{12}^i$.

The resulting immitance matrix of the two-stage three-parameter GIC_N is found by means of transfer equations [6]:

$$[A_\Sigma]=\begin{bmatrix} A_{11\Sigma} & A_{12\Sigma} \\ A_{21\Sigma} & A_{22\Sigma} \end{bmatrix}=\left[A^{(1)}\right]\times\left[A^{(2)}\right]=\begin{bmatrix} \dfrac{\Delta Y^{(2)}+Y_{12}^{(1)}\cdot Y_{12}^{(2)}}{Y_{21}^{(1)}\cdot Y_{21}^{(2)}} & \dfrac{Y_{12}^{(1)}+Y_{11}^{(2)}}{Y_{21}^{(1)}\cdot Y_{21}^{(2)}} \\ \dfrac{\Delta Y^{(2)}\cdot Y_{11}^{(1)}+\Delta Y^{(1)}\cdot Y_{12}^{(2)}}{Y_{21}^{(1)}\cdot Y_{21}^{(2)}} & \dfrac{\Delta Y^{(1)}+Y_{11}^{(1)}\cdot Y_{11}^{(2)}}{Y_{21}^{(1)}\cdot Y_{21}^{(2)}} \end{bmatrix}, \quad (12)$$

where $\Delta Y^{(1)}=Y_{11}^{(1)}\cdot Y_{22}^{(1)}-Y_{12}^{(1)}\cdot Y_{21}^{(1)}$, $\Delta Y^{(2)}=Y_{11}^{(2)}\cdot Y_{22}^{(2)}-Y_{12}^{(2)}\cdot Y_{21}^{(2)}$ – indicators of admittance matrices of the first and the second stages of GIC_N respectively.

Using reverse transformations, we pass to the admittance matrix of two-stage three-parameter GIC_N:

$$[Y_\Sigma]=\begin{bmatrix} Y_{11\Sigma} & Y_{12\Sigma} \\ Y_{21\Sigma} & Y_{22\Sigma} \end{bmatrix}=\begin{bmatrix} \dfrac{\Delta Y^{(1)}+Y_{11}^{(1)}\cdot Y_{11}^{(2)}}{Y_{12}^{(1)}+Y_{11}^{(2)}} & -\dfrac{\left(\Delta Y^{(1)}-Y_{11}^{(1)}\cdot Y_{12}^{(1)}\right)\cdot\left(\Delta Y^{(2)}-Y_{11}^{(2)}\cdot Y_{12}^{(2)}\right)}{Y_{21}^{(1)}\cdot Y_{21}^{(2)}\cdot\left(Y_{12}^{(1)}+Y_{11}^{(2)}\right)} \\ -\dfrac{Y_{21}^{(1)}\cdot Y_{21}^{(2)}}{Y_{12}^{(1)}+Y_{11}^{(2)}} & \dfrac{\Delta Y^{(2)}+Y_{12}^{(1)}\cdot Y_{12}^{(2)}}{Y_{12}^{(1)}+Y_{11}^{(2)}} \end{bmatrix}. \quad (13)$$

The converted admittance of the two-stage three-parameter GIC_N is described by the expression:

$$Y_{output.2}=Y_{22}^{(2)}-\frac{Y_{12}^{(2)}Y_{21}^{(2)}}{Y_{11}^{(2)}+Y_{output.1}}, \quad (14)$$

where

$$Y_{output.1}=Y_{22}^{(1)}-\frac{Y_{12}^{(1)}Y_{21}^{(1)}}{Y_{11}^{(1)}+1/Z_{G1}}. \quad (15)$$

Analytical dependences (13) – (15), which form the mathematical model of the multiparameter two-stage GIC_N, are vivid and effective for designing various types of information devices formed by a cascade connection of tripoles. The developed mathematical model describes the dependence of converted conduction of multistage GIC_N both on the number of stages N and on the values of the converted resistances ($Z_{G1}\ldots Z_{GN}$) as well as on the parameters of separate stages $[y^i]$. It also enables investigation of GIC_N properties while using any type of quasi-linear three-pole device irrespective of the frequency range.

Evaluation of adequacy of the mathematical model

Correctness of the developed mathematical model of two-stage multiparameter GIC_N was validated using the circuit of three-parameter two-stage GIC_N (Fig. 3), developed in [9], by comparison of the calculation results with those of simulation. The circuit of three-parameter two-stage GIC_N is formed on the basis of two stages of multiparameter GIC_N, where field-effect common-drain transistors VT1 of NE4210S01 type and VT2 of F513 type are used as basic tripoles.

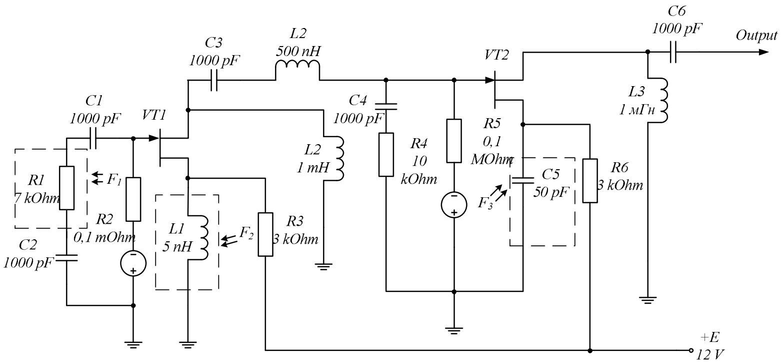


Fig. 3. Electrical principal circuit of three-parameter two-stage GIC

Between the gate and the common bus of transistor NE4210S01 a resistive primary measuring transducer (PMT) $Z_{G1} = R1$ is connected. Between the drain of this transistor and the common bus inductive PMT $Z_{G2} = j\omega L_1$ is connected; between the drain and the common bus of transistor BF513 capacitive PMT $Z_{G3} = 1/j\omega C_5$ is located.

Taking into account expressions (11), (14) and (15,) the converted admittance of the three-parameter two-stage GIC$_N$ will be given by:

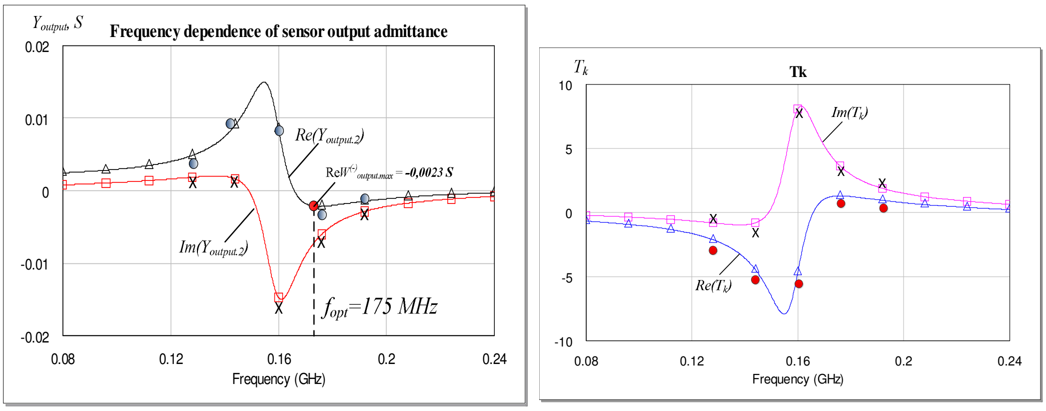
$$Y_{output.2} = \frac{y'_{22} + Z_{G3}\cdot\Delta y'}{Z_{G3}\cdot\sum y' + 1} - \frac{\left(y'_{12} - Z_{G3}\cdot\Delta y'\right)\cdot\left(y'_{21} - Z_{G3}\cdot\Delta y'\right)}{\left(Z_{G3}\cdot\sum y' + 1\right)^2\cdot\left[\frac{y'_{11} + Z_{G3}\cdot\Delta y'}{Z_{G3}\cdot\sum y' + 1} + \frac{y_{22} + Z_{G2}\cdot\Delta y}{Z_{G2}\cdot\sum y + 1} - \frac{\left(y_{12} - Z_{G2}\cdot\Delta y\right)\cdot\left(y_{21} - Z_{G2}\cdot\Delta y\right)}{\left(Z_{G2}\cdot\sum y + 1\right)^2\cdot\left(\frac{y_{11} + Z_{G2}\cdot\Delta y}{Z_{G2}\cdot\sum y + 1} + \frac{1}{Z_{G1}}\right)}\right]}. \quad (16)$$

The results of simulation and computation of frequency dependencies of the converted sensor conduction are presented in Fig. 4 a.

Comparison of the simulation and computation results have shown that disagreements are no more than 0,5%. Maximal negative value of the real component of the output admittance Re$W^{(-}_{output..max}$ is -0,0023 S (See Fig. 4 a) while error between the results of simulation and computation of this parameter does not exceed 0,42%.

Frequency that corresponds to the maximal value of Re$W^{(-)}_{output..max}$ = 0,0023 S for constant value of the converted immitances is optimal conversion frequency f_{opt} = 175 MHz. Error for this parameter is 0,57%.

Direct conversion coefficient T_k was the next parameter, for which the correctness of the developed mathematical model was examined. This coefficient is a complex quantity and is defined as $T_k = Y_{output2}/ Y_{G1}$, where $Y_{G1} = 1/ Z_{G1}$. Results of simulation and calculation are presented in Fig. 4 b.

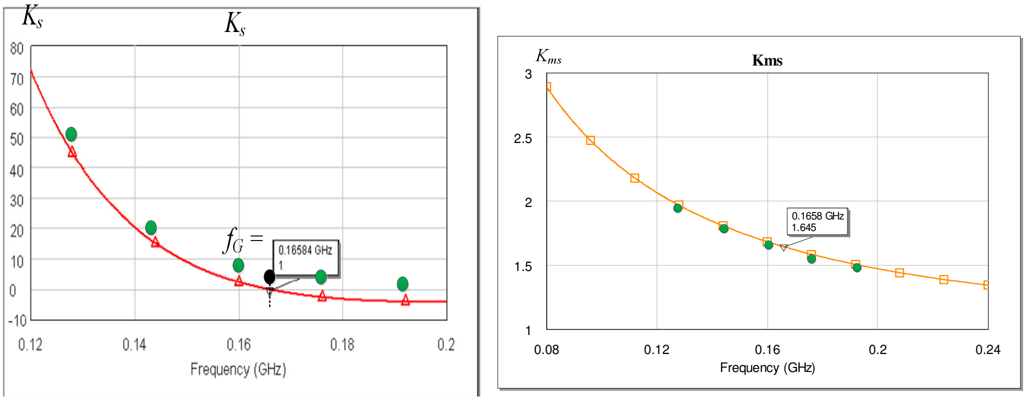


a) (b)

Fig. 4. Dependences of the converted admittance $Y_{output.2}$ (a) and conversion coefficient T_{kc} (b) in frequency range «——» - simulation; «×××» and «•••» - computation

Discrepancy of the results for real component of the direct conversion coefficient T_k in the frequency range from 0,08 to 0,24 GHz does not exceed 3,22% and for the imaginary component – 2,97 %.

Invariant stability coefficienti K_s is one of the main GIC$_N$ parameters. K_s values are within the interval (–1; +∞). Active quadripole is potentially stable if $K_{s.in} > 1$ and potentially unstable for $K_{s.in} < 1$. The value of $K_{s.in} = 1$ corresponds to the potential stability limit. Computation of the invariant stability coefficient was performed using expression (2) for loaded quadripole. As it is evident from Fig. 5a, two-stage multiparameter GIC$_N$ is a potentially unstable quadripole in frequency range from 165,8 MHz. For this frequency a maximal attainable numerical value of the power transfer coefficient at the stability margin K_{ms} (Fig. 5 б) is 1,645. Disrepancy between the results of simulation and calculation of the invariant stability coefficient is 1,1%.



a) b)

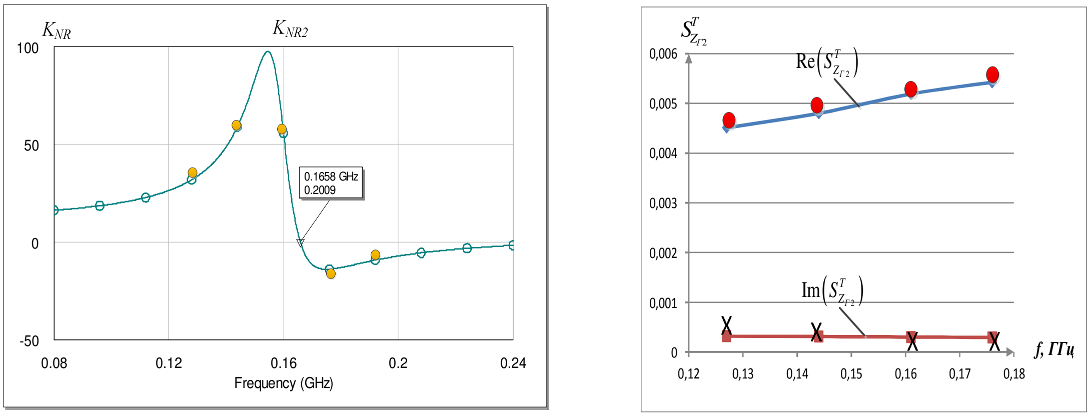
Fig. 5. Dependencies of the invariant stability coefficient K_S (a) and maximally attainable power transfer coefficient at the stability margin K_{ms} (b) in the frequency range: «——» - simulation; «•••» - computation

From the same graph it is evident that boundary frequency of the two-stage multi-parameter GIC$_N$ f_G (K_s = 1) is 165,8 MHz according to simulation results while the calculated value is f_G = *175* MHz. For this parameter error is 1,93%.

Fig. 5 b shows the results of computation and simulation of the maximally attainable power transfer coefficient at the stability margin K_{ms}. Calculated values of this parameter are obtained using formula $K_{ms} = |Y_{21}/Y_{12}|$. Discrepancy between simulation and computation results does not exceed 1,7%.

Non-reciprocity properties of GIC$_N$ could be quantitatively estimated by means of non-reciprocity coefficient K_{NR}. For potentially unstable GIC$_N$ it characterizes non-reciprocity properties of GIS$_N$ in the region of potential instability: $K_{NR}\ (K_s < 1) = \mathrm{Re}W_{22} / \mathrm{Re}W_{11}$.

The simulation and computation results of the non-reciprocity coefficient differ by the value of 0,22 % (Fig. 6).



a) b)

Fig. 6. Dependency of the non-reciprocity coefficient K_{NR} (a) and sensitivity of the conversion factor $S_{\alpha_i}^{T_k}$ to the variations of parameter $Z_{G2} = j\omega L_1$ (b) in the frequency range: «——» - simulation; «•••» - computation

Sensitivity of the conversion coefficient $S_{\alpha_i}^{T_k}$ to the variations of GIC$_N$ parameters is an indicator of N-polar quality. The smaller the value of GIC$_N$, the more qualitative it is. For experimental validation of the correctness of the developed GIC$_N$ mathematical model sensitivity of the conversion ratio $S_{\alpha_i}^{T_k}$ was investigated relative to the variations of parameter $Z_{G2} = j\omega L_1$. The results of simulation and computation are presented in Fig. 6 b.

Sensitivity of conversion ratio of the investigated GIC$_N$ does not exceed 0,006. Error between this parameter calculation and simulation values is 1,8 %. This means that three-parameter two-stage GIC$_N$ is qualitative as it has low level of the conversion ratio sensitivity to the influence of external destabilizing factors.

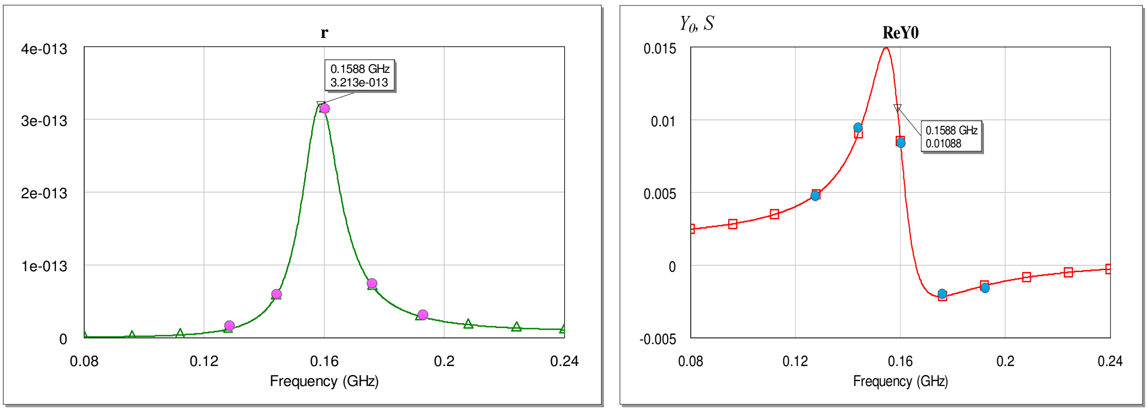
In accordance with the theory of conformal images [10] on a complex plane [10], the converted conduction of the multi-parameter two-stage GIC$_N$ could be represented in the form of a circle with radius ρ

$$\rho_{output} = \left| W_{12} \cdot W_{21} \right| / 2 \cdot Re(W_{11} + W_G), \tag{17}$$

And centre coordinate W$_0$ with active component

$$Re W_{output.0} = Re W_{22} - Re\left(W_{12} \cdot W_{21} \right) / 2\, Re(W_{11} + W_G). \tag{18}$$

The results of calculation and simulation of the immitance circuit parameters are presented in Fig. 7. The biggest radius of the immitance circuit ρ is observed at frequency 158,8 MHz (Fig. 7 a) while active component of the centre coordinate $Re\, Y_{output.0}$ at this frequency is 0,011 (Fig. 7 b).



a) b)

Fig. 7. Dependencies of the radius ρ variations (a) and active component of the centre coordinate $Re\,Y_{output.0}$ (b) of the output immitance circuit of the multiparameter two-stage GIC_N : «——» - simulation; «•••» - calculation

The bigger the immitance circuit radius, the wider functional capabilities of GIC_N for realization of different types of information control devices on its basis. Difference between the simulation and calculation results does not exceed 5%. At the same time the discrepancy between the calculation values and results of simulation of the real component of the output immitance circuit centre coordinate for the three-parameter two-stage GIC_N is 0,2 %.

Analysis of the simulation and calculation results of the definite system of parameters, that describes multiparameter GIC_N, confirms correctness of the developed mathematical model, the evidence of which is discrepancy not exceeding 5%. This indicates expediency of such model application for designing various information devices, which are formed by cascade connection of tripoles in the presence of real initial conditions.

Conclusions

Mathematical model of N-stage connection of multiparameter GIC_N has been elaborated. In contrast to the mathematical model of Babak L. I. [11], the developed model has a number of advantages, including the possibility of transition from the conduction matrix of one stage to general admittance matrix of several stages connection through the application of transition to transfer parameters. This mathematical model also describes dependence of the converted conduction of a multistage GIC_N both on the number of stages N and on the values of converted resistances ($Z_0 \ldots Z_N$) as well as on the parameters of separate stages [y^i], which makes it possible to perform calculations of various information devices formed by cascade connection of tripoles.

In order to confirm the correctness of the obtained analytical expressions, a number of determined parameters, describing main GIC_N properties, were investigated by the example of a two-stage three-parameter radiofrequency sensor. Comparative analysis of the results of simulation and main GIC_N parameters calculation has shown that the value of relative error is within the normal range and does not exceed 5%. This indicates the correctness of the developed mathematical model and expediency of its application for designing various types of information devices, formed by cascade connection of tripoles in the presence of real initial conditions.

REFERENCES

1. Филиппов А. В. Магнитоэлектрический гиратор / А. В. Филиппов, С. В. Белый, Джуни Жай, Г. А. Семенов // Научно-технический журнал «Вестник Новгородского государственного университета». – 2008. – № 46. – С. 54 – 56.

2. Бенинг Ф. Отрицательные сопротивления в электронных схемах / Ф. Бенинг. – М. : Сов. радио, 1975. – 288 с.

3. Пашаев А. М. Физико-технологические и схемотехнические основы негатроники / А. М. Пашаев, Ф. Д.

Касимов, Н. А. Филинюк, О. Н. Негоденко. – Баку : Элм, 2008. – 433 с.
4. Кравченко А. М. Двухканальный терморегулятор на основе S-негатронов / А. М. Кравченко, А. М. Анохин // Датчики и системы. – 2013. – № 2. – С. 28 – 32.
5. Ліщинська Л. Б. Інформаційні пристрої на основі багатопараметричних узагальнених перетворювачів імітансу: монографія. / Л. Б. Ліщинська. – Вінниця : ВНТУ, 2013. – 219 с.
6. Филановский Н. М. Схемы с преобразователями сопротивления / Н. М. Филановский, А. Ю. Персианов, В. К. Рыбин. – Л. : Энергия, 1973. – 192 с.
7. Ліщинська Л. Б. Математична модель узагальненого перетворювача іммітансу на базі трьохполюсника / Л. Б. Ліщинська // Вісник Тернопільського нац. тех. ун. – 2010. – т. 15, № 3. – С. 165 – 171.
8. Мокін Б. І. Математичні методи ідентифікації динамічних систем : навчальний посібник / Б. І. Мокін, В. Б. Мокін, О. Б. Мокін. – Вінниця : ВНТУ, 2010. – 260 с.
9. Сигорский В. П. Основы теории электронных схем / В. П. Сигорский, А. И. Петренко. – К. : Вища школа, 1971. – 568 с.
10. Лищинская Л. Б. Трёхпараметрический генераторный датчик / Л. Б. Лищинская, Н. А. Филинюк, Я. С. Ткачук, О. О. Лазарев // Научно-технический журнал "Технология и конструирование в электронной аппаратуре". – 2014. – Вип. 4. – С. 21 – 27.
11. Бабак Л. И. Определение матрицы рассеяния соединения СВЧ многополюсников / Л. И. Бабак // Радиотехника. – 1979. – Т. 34, № 11. – С. 78 – 81.

Tkachuk Yana – Post-graduate student of the Department of Computer and Telecommunication Equipment Design, rozhkova.yana@gmail.com.

Fursa Svitlana – Cand. Sc. (Eng.), Assist. Prof. of the Department of Computer and Telecommunication Equipment Design, pip_1@mail.ru.

Vinnytsia National Technical University.