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RESEARCH ARTICLE

Mathematical modeling of microwave channels of a semi-active radar homing head

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Abstract
Objectives. Radar homing heads of guided missiles form a large group of radars which differ from other radars due to their specific purpose. The advantages of a semi-active radar homing head (SARH) include the ability to have a powerful irradiator at the command post and, as a result, a powerful reflected signal from the target. This results in an increase in the range of its detection and guidance. The absence of an emitter simplifies the missile's onboard control equipment, reduces its weight and dimensions, thereby improving its maneuverability and increasing the guidance accuracy, resulting in the greatest distribution of this type of SARH. However, in order to determine the exact Doppler shift of the target signal as part of SARH, a reference signal with a frequency coinciding with the illumination transmitter signal must be supplied to the receiving path. This study aims to synthesize and analyze the SARH receiver circuit with improved accuracy characteristics.
Methods. The following methods are used: statistical radio engineering; optimal signal reception theories; and computer modeling in CAD *AWR Design Environment*.
Results. A mathematical model of the SARH receiver was obtained and analyzed. The proposed receiver model allows the spectral characteristics of signals to be calculated at any point of the microwave paths, as well as signal characteristics at the input of the head channel, at the output of the first conversion mixer, at the output of the first intermediate frequency selector, and at the output of the receiving path. The calculated values of the main characteristics of high-frequency channels are also given.
Conclusions. The resulting model allows the frequency dependencies of main parameters of the receiving path, such as the gain factor, noise factor, decibel compression points, and third-order intermodulation intercept points to be estimated. The values obtained during the simulation are maximally close to existing systems, since the models of real-life and mass-used microcircuits thu created are used as the main elements when designing high-frequency paths. The model can be used to study methods of improving technical indicators, as well as to develop new principles and schemes for developing radioelectronic complexes, for example, when designing a receiving path using advanced radio photonics.

Keywords: semi-active radar homing head, microwave receiver, receiver characteristics, modeling

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НАУЧНАЯ СТАТЬЯ

Математическое моделирование сверхвысокочастотных каналов полуактивной радиолокационной головки самонаведения

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Резюме

Цели. Радиолокационные головки самонаведения (РГСН) управляемых ракет – это большая группа радиолокаторов, которые в виду особенностей назначения отличаются от других радиолокаторов. Преимуществом полуактивной РГСН является возможность иметь мощный облучатель на командном пункте и, как следствие, мощный отраженный сигнал от цели, что в результате приводит к увеличению дальности ее обнаружения и точности наведения на цель. Отсутствие аппаратуры излучения упрощает бортовую аппаратуру управления ракеты, уменьшает ее вес и габариты и, следовательно, улучшаются ее маневренные свойства, что обуславливает наибольшее распространение данного типа РГСН. Для точного определения доплеровского смещения сигнала цели в приемный тракт полуактивной РГСН должен поступать эталонный сигнал, частота которого совпадает с частотой сигнала передатчика подсвета. Цель работы – оптимизация бортовой аппаратуры и подтверждение предлагаемого подхода с помощью моделирования.

Методы. В работе использованы методы статистической радиотехники, теории оптимального приема сигналов и компьютерное моделирование в системе автоматизированного проектирования *AWR Design Environment*.

Результаты. Получена и проанализирована математическая модель приемника РГСН. Предложенная модель приемника позволяет произвести расчет спектральных характеристик сигналов в любой точке СВЧ-трактов, характеристик сигналов на входе основного канала, на выходе смесителя первого преобразования, на выходе селектора первой промежуточной частоты и на выходе приемного тракта. Приведены расчетные значения основных характеристик высокочастотных каналов.

Выводы. Полученная модель позволяет оценивать частотные зависимости основных параметров приемного тракта, таких как коэффициент передачи, коэффициент шума, точки децибельной компрессии, точки пересечения интермодуляций третьего порядка. Полученные при моделировании значения максимально приближены к характеристикам существующих систем, т.к. в качестве основных элементов высокочастотных трактов использовались созданные модели реально существующих и массово используемых микросхем. Модель может использоваться для исследования путей совершенствования технических показателей, разработки новых принципов и схем построения радиоэлектронных комплексов, например, при построении приемного тракта с использованием перспективных средств радиофотоники.

Ключевые слова: полуактивная радиолокационная головка самонаведения, СВЧ-приемник, характеристики приемника, моделирование

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INTRODUCTION

Radar homing heads (RH) of guided missiles form a large group of radars which differ from other radars due to their specific purpose [1–3]. A distinction is made between active (ARH) and semi-active radar homing heads (SARH). Each type has its own advantages and disadvantages. In the case of active homing, a missile using RH irradiates the target and receives part of the reflected energy by means of a single antenna, active [4], or digital [5] phased antenna array. The information (energy) received is processed by RH and output as control signals to the missile autopilot.

The advantage of SARH is its ability to create a powerful irradiator at the command post and, consequently, a powerful reflected signal from the target. This results in increased detection range and targeting accuracy. The absence of a microwave signal generator simplifies the onboard control equipment of the missile, and also reduces its weight and dimensions, hence improving its maneuverability. As a result, SARH is widely used.

FUNCTIONAL DIAGRAM AND MATHEMATICAL DESCRIPTION OF SARH

A variety of modeling packages and technologies are used to work out most efficient solutions of SARH modules [6–9].

The basic concept behind semi-active homing heads is that since almost all detection and tracking systems contain ground-based radar systems, duplication of this equipment on the missile itself in some cases is redundant. In order to synchronize the SARH hardware, the ground-based radar signal can be used as a reference signal. In order to determine the Doppler shift of the target signal as part of SARH, a reference signal with a frequency coinciding with that of the illumination transmitter signal should be fed into the receiving path. The solution to this problem is the use of a direct signal (reference signal) received by a special antenna, propagating from the transmitter of the ground radar station towards SARH. In order to receive this signal, a special reference receiver is added to SARH to amplify the signals received by the reference signal antenna oriented to the rear hemisphere of the missile, i.e., towards the illumination station. The amplified reference signal is used for heterodyne synchronization in SARH or directly as a heterodyne signal in the receiver [10].

The functional diagram of the SARH receiver is shown in Fig. 1 [6]. The illumination station radiates a signal with frequency f_0. The frequency $f_{\text{ref.ch.}}$ of the signal received by the reference channel is shifted downward due to the Doppler effect when the missile moves away from the illumination station, as follows:

$$f_{\text{ref.ch.}} = f_0 - \frac{V_\text{r}}{\lambda}, \tag{1}$$

where f_0 is the illumination station signal frequency, V_r is the missile radial velocity, λ is the reference signal wavelength.

The frequency of the target signal received by the reference channel is shifted upward due to the oncoming motion of the missile and target, as follows:

$$f_{\text{head ch.}} = f_0 + \frac{V_\text{r}}{\lambda} + \frac{V_\text{t}}{\lambda}, \tag{2}$$

where $f_{\text{head ch.}}$ is the frequency of the signal as reflected from the target received by the head (main) channel; V_t is the target velocity.

Both the signal reflected from the target and the reference signal are converted to the first intermediate frequency using the common first heterodyne signal f_{h1}, as follows:

- first intermediate frequency of the reference channel

$$f_{\text{ref.ch.1}} = f_0 - \frac{V_\text{r}}{\lambda} - f_{\text{h1}}, \tag{3}$$

- first intermediate frequency of the head channel

$$f_{\text{head ch.1}} = f_0 + \frac{V_\text{r}}{\lambda} + \frac{V_\text{t}}{\lambda} - f_{\text{h1}}. \tag{4}$$

The reference signal $f_{\text{ref.ch.1}}$ cannot be directly used as a heterodyne signal in the further processing

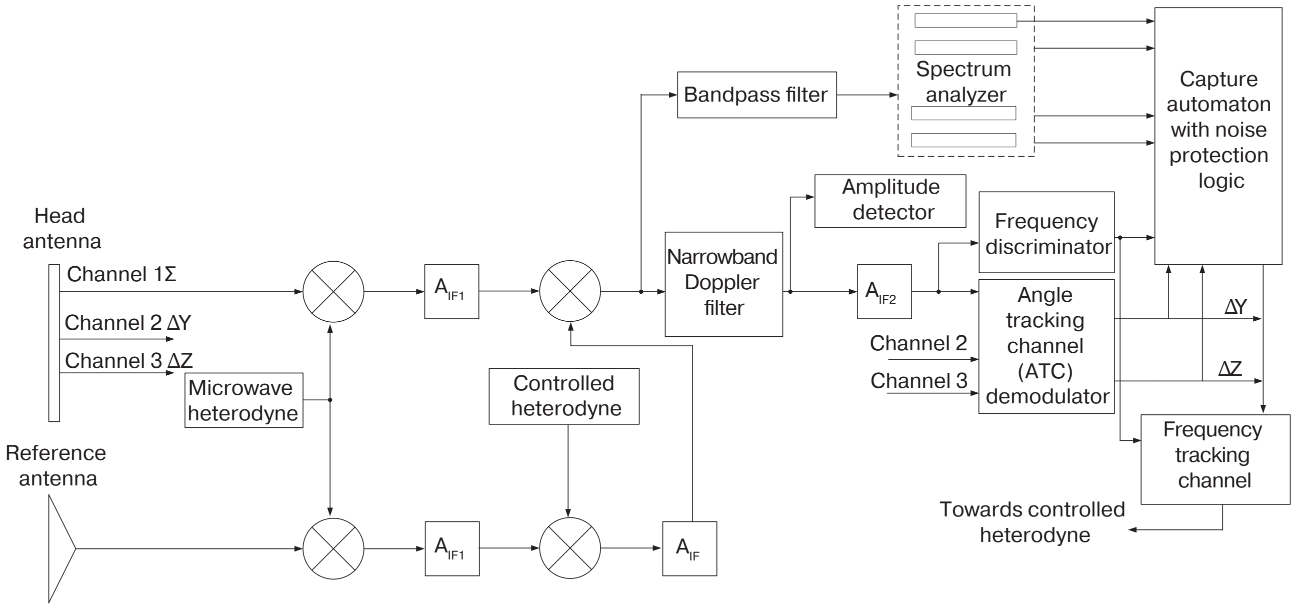

Fig. 1. Functional diagram of the SARH receiver. ATC is the angular tracking channel; A_{IF}, A_{IF1}, and A_{IF2} are intermediate frequency amplifiers

of the head channel signal, since in this case, the signal conversion occurs at low frequencies, where for circuitry reasons processing is difficult. In order to prevent this, the reference signal is shifted to the second intermediate frequency using an additional controlled heterodyne. The frequency of the controlled heterodyne signal may be written as follows:

$$f_{\text{c.h.}} = f_{\text{IF2}} + f_{\text{DF}}, \quad (5)$$

where f_{IF2} is a fixed value equal to the second intermediate frequency of the head channel; and f_{DF} is the predicted value of the Doppler frequency of the target signal received from the target channel or as a result of target tracking.

The second intermediate frequency of the reference channel is equal to the following:

$$f_{\text{ref.ch.2}} = f_0 - \frac{V_{\text{r}}}{\lambda} - f_{\text{h1}} + f_{\text{IF2}} + f_{\text{DF}}. \quad (6)$$

Signal $f_{\text{ref.ch.2}}$ is used as a heterodyne signal in further conversion of head channel signals in the so-called convolution mixer, and since frequency $f_{\text{ref.ch.2}}$ is higher than $f_{\text{head ch.1}}$, the frequency of the second signal is subtracted from the first, as follows:

$$f_{\text{head ch.2}} = f_{\text{ref.ch.2}} - f_{\text{head ch.1}} = \\ = f_{\text{IF2}} + f_{\text{DF}} - \frac{2(V_{\text{r}} - V_{\text{t}})}{\lambda}. \quad (7)$$

Here $f_{\text{head ch.2}}$ is the signal frequency of the second intermediate frequency of the head channel, while the actual Doppler shift of the target signal may be written as follows:

$$\frac{2(V_{\text{r}} - V_{\text{t}})}{\lambda} = f_{\text{d}}. \quad (8)$$

Since term f_{d} represents the actual Doppler shift of the target signal, the frequency of the signal after conversion is shifted relative to f_{IF2} by the difference between the predicted and actual Doppler frequency values. When they are equal, it falls exactly on f_{IF2}. When processing the target signal, this allows use of the narrowband Doppler filter tuned to the fixed value of frequency f_{IF2}, irrespective of the Doppler shift of the target signal. The principle of operation and SARH functional diagrams are described in more detail in [6].

MATHEMATICAL MODELING OF SARH MICROWAVE CHANNELS

In order to calculate the characteristics of SARH microwave channels, closest to the real ones, the characteristics of real existing microcircuits and systems of radar stations are used for modeling [11–17].

Applying the *Visual System Simulator* (*VSS*) module of the *AWR Design Environment*[1] system for computer-aided design and modeling of high-frequency (HF) systems and devices enables the work at the design stage to be automated, and the main characteristics of microwave channels to be calculated. The model of SARH microwave channels developed in the *VSS* environment is shown in Fig. 2.

The first functional block in the SARH receiving path is the input power limiter. It reduces the signal level

[1] https://pcbsoftware.com/product/awr/. Accessed September 13, 2023.

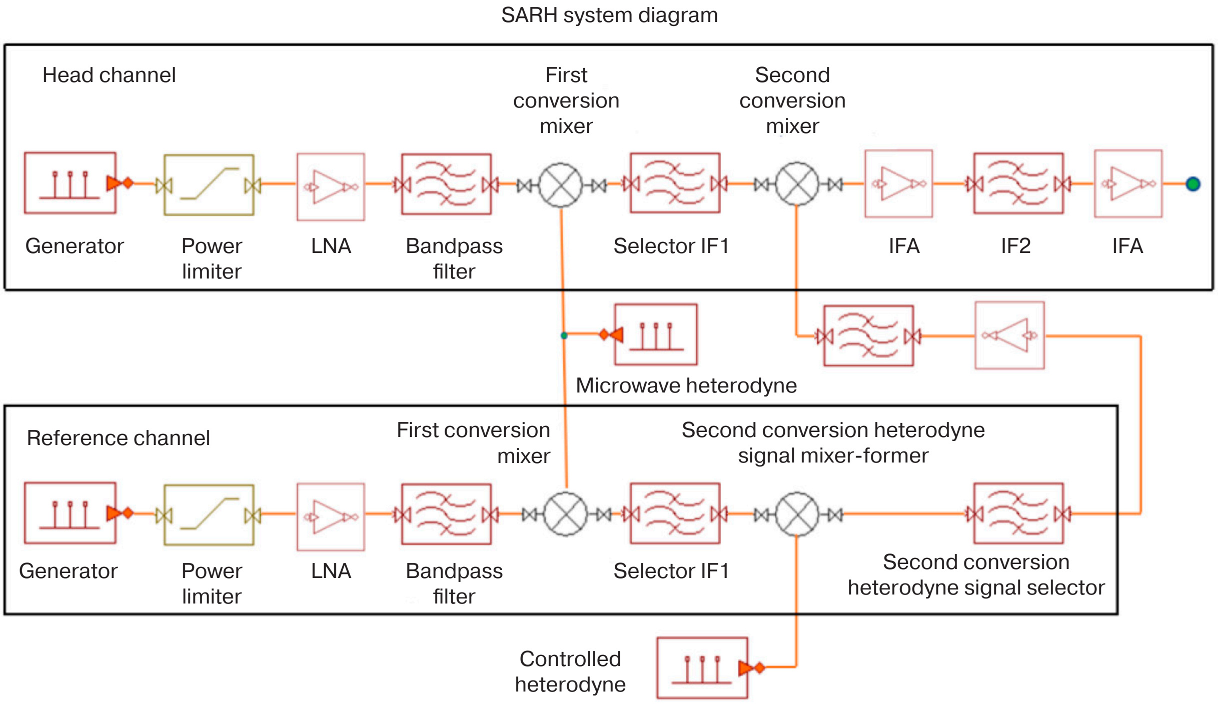

Fig. 2. Model of SARH microwave channels

entering the low-noise amplifier (LNA) to a safe level. The TGL2208-SM[2] chip is used as a power limiter. In order to achieve the required transmission coefficient, a multi-stage construction scheme of the receiving path is used. Each stage amplifies the incoming signal in accordance with its gain factor G and has its own noise level characterized by noise factor F.

The formula for determining the noise factor of the stage amplifier is given in [14] and has the following form:

$$NF = NF_1 + \frac{NF_2 - 1}{G_1} + \ldots + \frac{NF_n - 1}{G_{n-1}}, \tag{9}$$

where NF is the noise factor, F_1 is the noise factor of the first stage, F_n is the noise factor of the nth stage, G_1 is the gain factor of the first stage, and G_n is the gain factor of the nth stage.

The formula shows that the largest contribution to the total noise factor is made by the noise of the first stage. Furthermore, the higher the gain factor of the first stage, the lower the total noise factor.

Since the mixers where the frequency conversion occurs are quite noise intensive, the very first gain stage (LNA) is performed before the frequency conversion, i.e., at the carrier frequency. During modeling, the parameters of the QPA2609[3] chip are used as LNA.

The intermediate frequency amplifier (IFA) provides for maximum amplification of the received signal. The IFA brings the signal level to the value necessary for normal operation of the signal processing equipment, thus providing the necessary sensitivity for the receiver. The PMA3-83LN+[4] chip is used as IFA.

The mixer is used to gain the received carrier frequency signal to the intermediate frequency. The HMC773ALC3B[5] chip is selected as the mixer.

During modeling, the calculation of the main characteristics of microwave channels is carried out under normal climatic conditions. This includes the frequency dependencies of the gain factor ($S21$), noise factor (NF), decibel compression points (OP1dB), and third-order intermodulation cross points (OIP3).

The following frequencies are specified, in order to calculate the main parameters of the model: the operating frequency of the illumination station F_{il} (8 GHz); the frequency of the signal reflected from the target F_{refl}; the frequency of the first (reference) microwave heterodyne F_{h1}; and the frequency and bandwidth of signal processing (1 GHz). Signals F_{il} and F_{refl} are formed by library models of signal sources TONE and are fed to the input of the reference and main channel, respectively. Here they are reduced (if necessary) to a safe level by the first element of

[2] https://www.qorvo.com/products/p/TGL2208-SM. Accessed September 13, 2023.

[3] https://www.qorvo.com/products/p/QPA2609. Accessed September 13, 2023.

[4] https://www.minicircuits.com/pdfs/PMA3-83LN+.pdf. Accessed September 13, 2023.

[5] https://www.micro-semiconductor.com/datasheet/46-HMC773ALC3B.pdf. Accessed September 13, 2023.

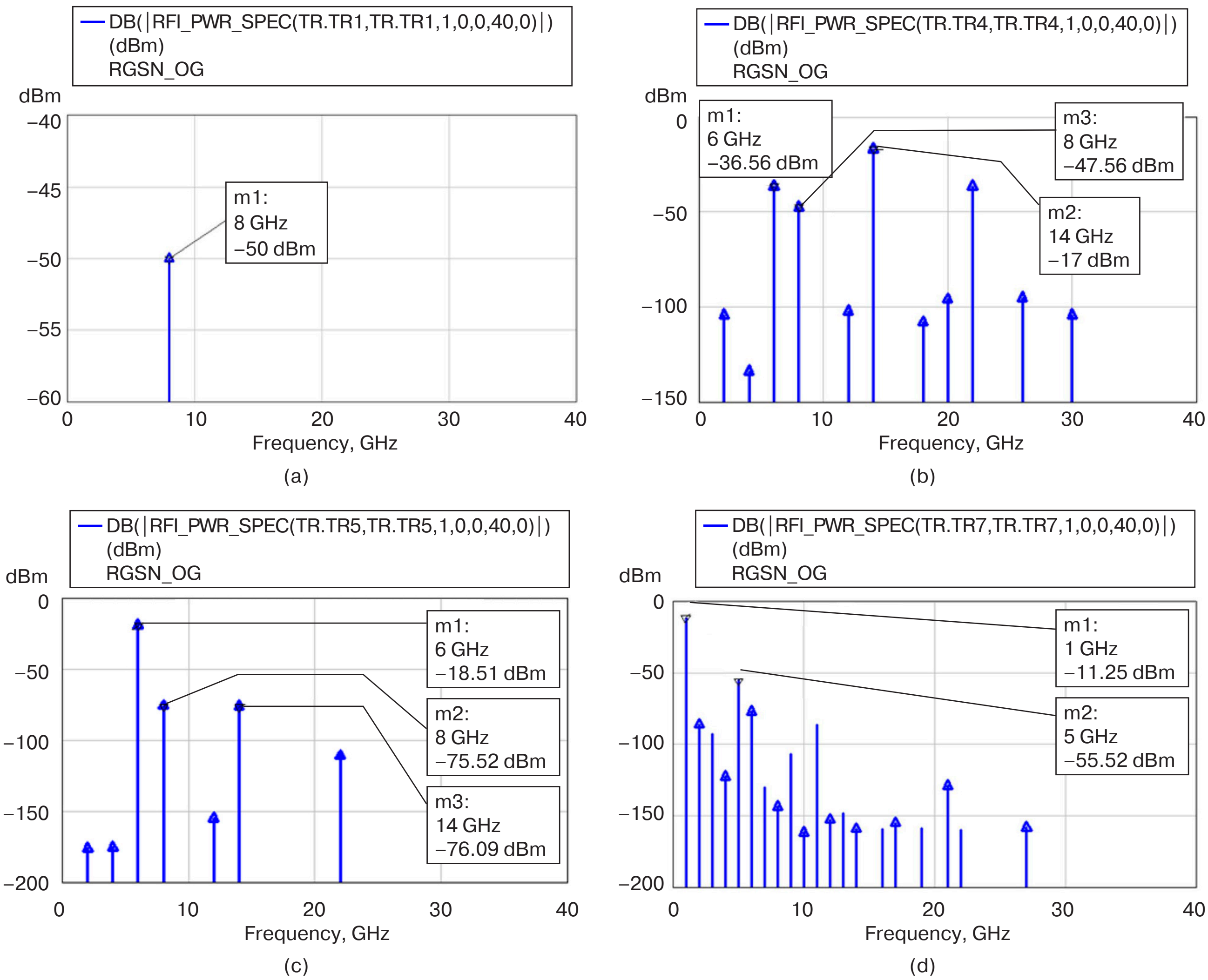

Fig. 3. Signal spectra: (a) at the input of the head channel, (b) at the output of the first conversion mixer, (c) at the output of the first intermediate frequency selector, (d) at the output of the receiving path

the receiving path that is TGL2208-SM power limiter. The safe level signals are fed to the QPA2609 LNA input and then to the input of the bandpass filter which separates the signals of the receiver working range. Signals are fed from the range filter output to the first conversion mixers where they are mixed with the microwave heterodyne signal F_{h1}. Then they are transferred to the spectrum of the first intermediate frequency signals $F_{IF\ up}$ and $F_{IF\ low}$ in the upper head (original) channel and in the lower reference (providing) channel, respectively. The operating frequency is selected by the first intermediate frequency selector, the bandwidth of which is changed in accordance with the specified equations depending on the illumination station operating frequency F_{il}.

The signal $F_{IF\ low}$, amplified in IFA, is transferred by the mixer-former to the signal frequency spectrum of the second heterodyne F_{h2} using the controlled heterodyne. The operating frequency is selected by the signal selector of the second heterodyne, while the signal level is increased to the required level in the IFA chain. Signal F_{h2} is fed to the heterodyne input of the second conversion mixer, to which signal $F_{IF\ up}$ is also fed, and then transferred to the signal processing frequency.

The resulting model allows the spectral characteristics of signals at any point of microwave paths to be calculated. The spectra of signals at the head channel input, at the first conversion mixer output, at the first intermediate frequency selector output, and at the receiving path output are shown in Fig. 3. The calculated values for main characteristics of HF channels are presented in Fig. 4.

By analyzing the graphs shown in Figs. 3 and 4, it can be concluded that the head channel receiving path in the configuration shown in Fig. 2 has a gain factor of at least 38 dB with an output decibel compression point level of at least 13 dBm.

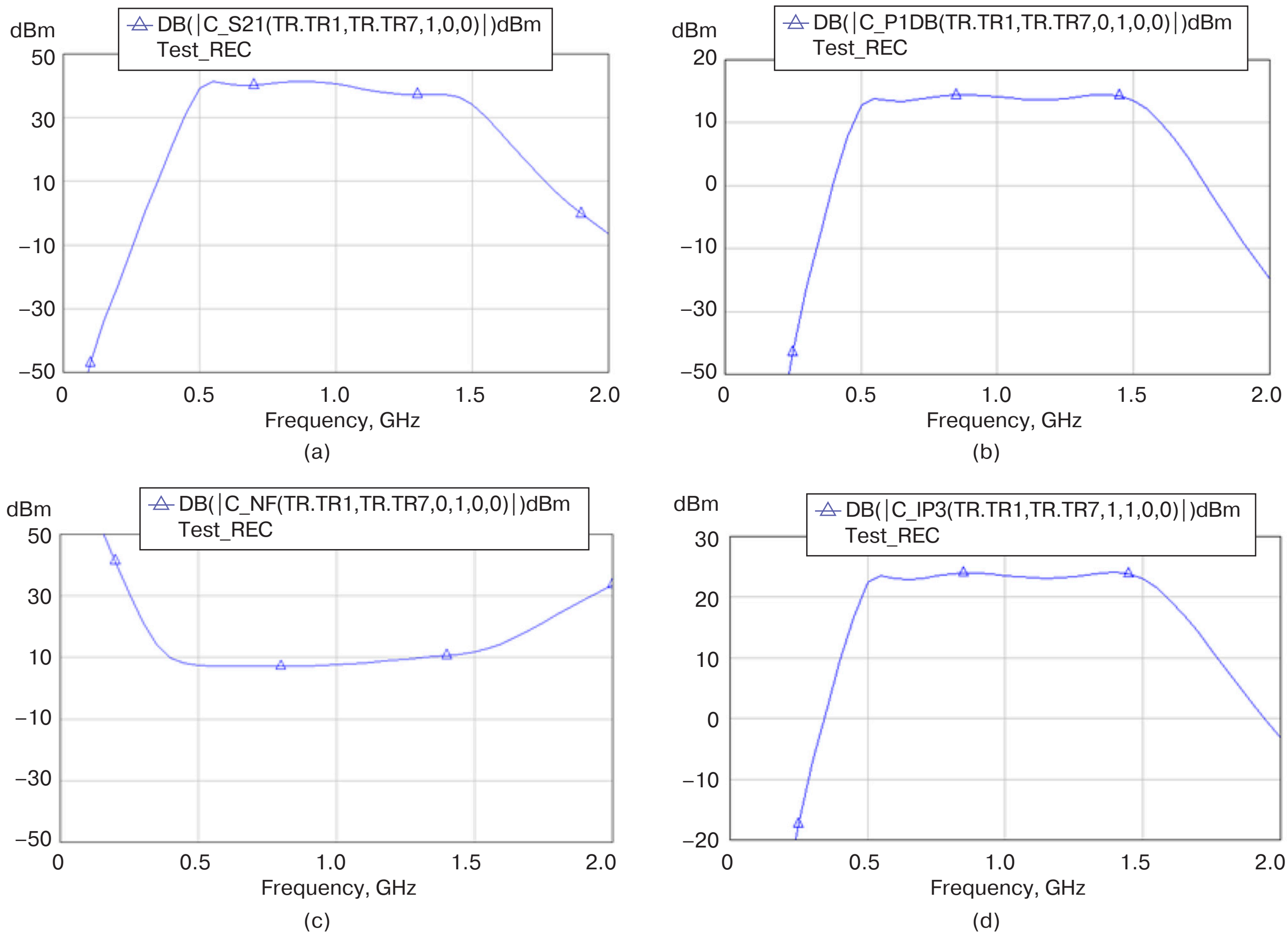

Fig. 4. Calculated values for the main HF channel characteristics:
(a) head channel gain factor, (b) head channel OP1dB, (c) noise factor *NF*, and (d) OIP3

CONCLUSIONS

The resulting model allows the frequency dependencies of the receiving path main parameters, such as gain factor, noise factor, decibel compression points, and third-order intermodulation cross points to be estimated. The simulation values are maximally close to those of existing systems due to using models of real widespread microcircuits as the main elements in constructing HF paths. The model can be used to study ways of improving the technical performance, as well as in the development of new principles and construction schemes for radioelectronic complexes (in particular, SARH), e.g., in constructing the receiving path using promising means of radio photonics.

Authors' contribution. All authors equally contributed to the research work.

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