Noise Characteristics Of Signal Generators Of Radio Transmitters For Wireless Ad-Hoc Communication Networks

Kuzichkin O.R.[1], Surzhik D.I.[2], Vasilyev G.S.[3]

[1] Belgorod State University, Belgorod/308015, Russia; Email: oldolkuz@yandex.ru
[2] Vladimir State University, Vladimir/600000, Russia
[3] Belgorod State University, Belgorod/308015, Russia

Abstract

This article is devoted to the study of noise characteristics of signal generators of radio transmitters of unmanned aerial vehicles of wireless ad-hoc communication networks. It is noted that the quality of transmitted payload data depends largely on the ability to adapt the speed of their transmission, determined by solutions at the physical level of the OSI network model. Based on the results of the analysis of carrier frequencies and digital modulation methods used for data transmission using unmanned aerial vehicles, a universal approach to signal formation is proposed, combining the advantages of the indirect modulation method with the frequency conversion up using a superheterodyne and the direct digital synthesis method; a generalized block diagram is developed that implements it. It is shown that one of the most important parameters of any signal generation system is the phase noise, for which mathematical models of noise characteristics are obtained. Based on the results of modeling the noise properties of the device, it was found that this scheme is characterized by a level of phase noise in minus 100 - minus 115 dBc/Hz at the offset of 1 kHz from the carrier oscillation for the generated signals in the frequency range of 1200-5800 MHz, which confirms the effectiveness of its use. Ways for further improvement the spectral characteristics of the signal transmitters of unmanned aerial vehicles are proposed. They include optimizing the circuit implementation for lowering the phase noise level, as well as automatic compensation of phase distortions that reduce the level of parasitic discrete spectral components in the output spectrum of the device by 10-15 dB.

Keywords*: wireless ad-hoc networks, unmanned aerial vehicles, signal generators, digital computing synthesizers, phase noise.*

1. Introduction

One of the promising directions for the development of infocommunication technologies in modern conditions is the creation and active use of wireless mobile ad-hoc networks (MANET) and their special case - ad-hoc networks of aircraft (Flying Ad-Hoc Network, FANET) [1-3], designed for network interaction using unmanned aerial vehicles (UAVs). The peculiarity of these data transmission networks is their variable topology and the absence of a permanent structure, which allows for high-quality communication between mobile objects, scalability and rapid recovery of the reference network due to the ability to quickly create additional nodes, as well as to ensure optimal coverage of the served territory by moving network nodes in the air and taking off at the maximum allowed height.

The ability to equip the network nodes of the MANET communication with additional onboard load (technical equipment, sensors, photo and video cameras, etc.) makes them an effective means of performing flight tasks in various spheres of human activity, one of which is the collection of data for geo-ecological monitoring of resources from the objects of the agro-industrial complex [4]. Due to their specific advantages, UAV-based MANET allow solving a wide range of tasks [5] in the field of agriculture, while reducing the risks arising in the course of agricultural activities by:
- creating accurate three-dimensional terrain models for soil analysis and planning seed planting schemes,
- using them for direct sowing of seeds, which reduces the cost of sowing by 85%;
- control of irrigation systems and nitrogen control, as well as direct spraying of plantings, which reduces the amount of excess chemicals entering the soil and is produced five times faster than using traditional techniques;
- collecting data for calculating the vegetation cover index, which allows assessing the current state of crops and predicting their changes;

- monitoring fields at all stages of the crop life cycle to prevent plant death and disease, as well as determining the optimal harvest time.

The successful implementation of these functions, as well as ensuring high-quality and reliable communication using UAV-based MANET, largely depends on the ability to adapt the payload data transfer rate determined by solutions at the physical level of the OSI network model by selecting the carrier frequencies of transmitted radio signals, as well as modulation and encoding methods [6-10]. In this aspect, it is relevant to develop universal approaches to the construction of signal generators for UAV radio transmitters that allow generating signals in a wide range of frequencies with the ability to quickly change the modes of modulation and encoding, as well as to study their most important characteristics.

2. Features of payload data transmission using UAV-based wireless ad-hoc networks

At the moment, high-speed data transmission (tens and hundreds of Mbit/s) is commonly possible in frequency bands higher than 1 GHz. At the same time, the most popular and widespread frequencies for transmitting payload data from a UAV are those near the central values of the 1.2 GHz, 2.4 GHz, and 5.8 GHz carriers [6-10]. Their popularity is due to the fact that they are regulated by law in most countries around the world, are characterized by good penetration of electromagnetic waves and their protection from interference of natural and artificial origin, as well as allow us to get small size of antennas and increase the efficiency of radiation.

In terms of transmission speed, various methods of digital phase modulation are the most effective: BPSK, QPSK, 8-PSK, 16-APSK and their derivatives, as well as variations of quadrature amplitude modulation (QAM), which differ in both spectral and energy efficiency [6-10].In addition, encoded signals with orthogonal frequency multiplexing (OFDM) can be used for simultaneous communication with multiple UAVs or, for example, for transmitting high-quality high-resolution images in Full HD format), allowing to provide data transfer speeds of 65 Mbit / s, and in the future — up to 274 Mbit/s.

The choice of the modulation method depending on the communication distance, the speed of the UAV and the specific interference situation allows to obtain different data transfer rates. As an example, the maximum achievable information exchange rates in OFDM mode in accordance with the IEEE 802.16 standard are: 6 Mbit/s in BPSK modulation mode, 15 Mbit/s in QPSK mode; 22.5 Mbit/s in 8-PSK mode; 30 Mbit/s in 16-QAM or 16-PSK mode, and 65.5 Mbit/s in 64-QAM mode.

The complexity of adaptive changes in the carrier frequency of the transmitted signal and the method of modulation used is largely determined by the lack of a single universal approach to signal formation in UAV radio transmitters.

At the moment, signal generators of UAV radio transmitters are built on the basis of several traditional schemes [11]: with direct modulation, with direct quadrature modulation, with indirect modulation based on frequency conversion up using a superheterodyne, and with the use of digital digital synthesizers (DDS). Schemes with direct quadrature modulation are characterized by maximum simplicity of implementation, but their main disadvantage is instability of the carrier oscillation and, as a result, presence of significant distortions in the generated signal. To overcome this disadvantage, several solutions can be applied in practice, the most popular of which is the scheme of indirect modulation with frequency conversion up using a superheterodyne. This solution allows to obtain acceptable spectral characteristics of the generated signal and low power consumption of the modulator due to the use of a relatively low intermediate frequency. The disadvantages of this approach, significant for UAV radio transmitters, are technological complexity of manufacturing filters and the need to generate two different frequencies. An effective way to overcome these disadvantages is to use a DDS that has the following key advantages compared to other solutions [12-20]:
- high resolution in frequency and phase, which is controlled digitally;
- high speed of frequency tuning without phase discontinuities and voltage surges in the output caused by the transition;
- the DDS architecture does not require precise clock frequency tuning due to the very small step of tuning the synthesizer frequency;
- digital interface makes it easy to implement microcontroller control;

- DDS are able to form quadrature modulated signals directly in the process of frequency synthesis.

Among the disadvantages of signal generators of this class, we should note the relatively high level of spurious spectral components in the spectrum of the synthesized oscillation, as well as the restriction on the maximum synthesized frequency, which is currently limited to a value of 1.7 GHz.

A special feature of the digital modulation methods for data transmission using UAVs is the need to form quadrature components for both the carrier and information signals. The method of indirect modulation with frequency conversion up using a superheterodyne is characterized by high spectral characteristics, but is not sufficiently technological, and DDSs have quadrature outputs for modulated signals, but have a limit on the maximum synthesized frequency. Due to this fact, it is proposed to combine the advantages of these methods of signal formation. As a result, we can draw a generalized structural diagram of the universal signal generator of the UV radio transmitter, shown in Fig. 1, where the following designations are accepted: RG - reference generator, FM1 and FM2 - frequency multipliers of the reference oscillation, LPF1 and LPF2 - antialiasing low-pass output filters for the DDS, I and Q-quadrature outputs of the DDS, QM-quadrature modulator.

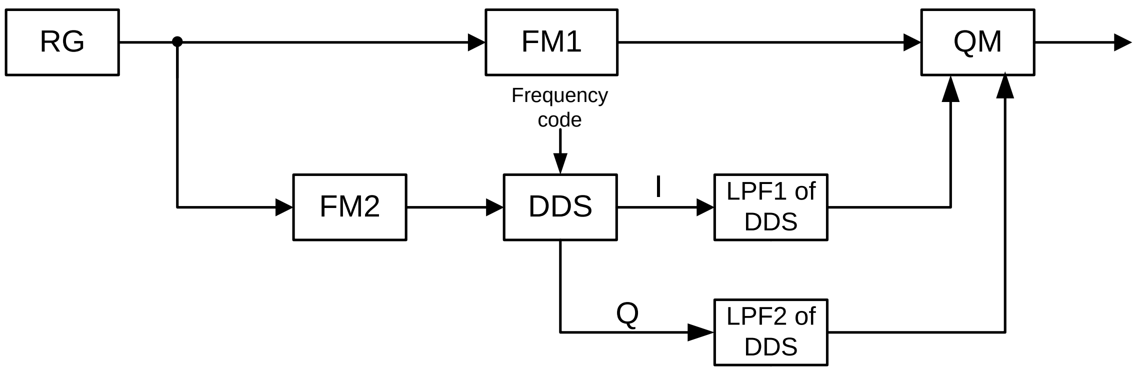


Fig. 1. Generalized block diagram of the universal signal generator of the UAV radio transmitter

In this scheme, it is recommended to use a highly stable reference frequency source based on a precision quartz oscillator as a reference generator, the value of which should not exceed 20 MHz to obtain an acceptable power consumption of the radio transmitter [11]. In addition, this solution allows to ensure coherence of the input signals of the QM for each of the circuit channels. The frequency multiplier FM1 is designed to obtain the necessary value of the carrier frequency and can be effectively implemented by a phase-locked loop (PLL), the frequency multiplier FM2 is used to obtain the clock frequency of the DDS, which must be at least twice the upper frequency of its output spectrum. Output low pass filters of DDSs in the generalized block diagram eliminate spurious components beyond the clock frequency of DDSs in their output spectrum, and the quadrature modulator QM is a versatile device, which can produce signals with virtually all modulation types used in modern wireless communication systems.

3. Mathematical models of noise characteristics of a universal signal generator of the UAV radio transmitter

One of the most important parameters of any signal generation systems is phase noise, which has a significant impact on their output characteristics. The main measure of this level is the power spectral density (PSD) [21-25] $S_\varphi(F)$ of the output signal near the carrier frequency, depending on the offset F at different values of the output frequency.

To study the noise characteristics of the proposed universal signal generator of the UAV radio transmitter (Fig. 1), its equivalent linearized functional scheme with all sources of active phase noise is compiled, presented in Fig. 2, for which it is assumed that FM1 is a PLL synthesizer, and FM2 is a transistor frequency multiplier. The following designations are used in the scheme: Φ_i - phase deviations of the corresponding blocks of the signal generator; n - multiplication factor of the transistor frequency multiplier of the reference generator; K_{DDS} - transmission coefficient of the DDS; K_D is the slope of the phase characteristic of the loop detector of the PLL;

K_{VCO} - slope of the modulation characteristic of the voltage-controlled oscillator (VCO) of a PLL loop; N is the division ratio of the frequency divider (Div) of the PLL loop; $M(p)$ is the transmission coefficient of the low pass filter of PLL; p - Laplace operator. In this scheme, multiplication of its output phase noise by two is used to account for the presence of two quadrature outputs of the DDS.

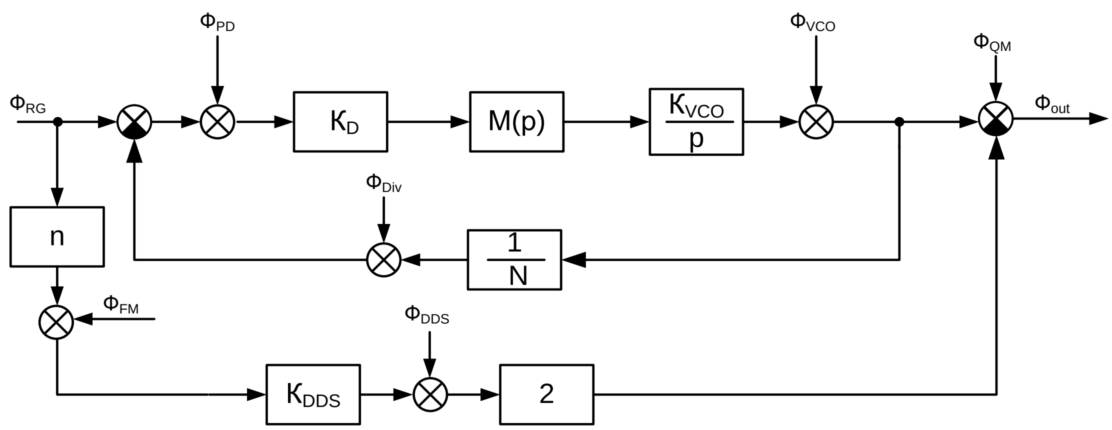


Fig. 2. Equivalent functional diagram of the signal generator of the UAV radio transmitter with all sources of phase noise

Since all the noise generated or added by each component of the circuit is small compared to the power of the useful signal, then according to the overlay rule, they can be added to the corresponding input or output effects. As a result, the resulting mathematical model of noise characteristics will be determined by the equivalent circuit (Fig. 2) and the following analytical expression

$$S_{out} = \sum_{i=1}^{I} S_i \left|H_i\right|^2 ,\ldots\ldots \quad (1)$$

where I is the number of signal generator block, i is the number of the current signal generator block, S_i is the PSD of the i–th block's own phase noise, and H_i is the transfer function of the i–th block.

To describe theoretically the level of phase noise of individual signal generator units we use approximation of the PSD of their phase noise by power functions in accordance with the universal model

$$S_{\varphi}(F) = \begin{cases} \sum_{\alpha=-2}^{+2} h_{\alpha} F^{\alpha}, \; 0 \le F \le F_h, \\ 0, \quad F > F_h, \end{cases} \quad (2)$$

where F_h is the upper boundary frequency of a sharp decline; h_{α} is a constant that serves as a measure of the level of phase noise.

Let's consider typical relations for calculating the PSD of phase noise of various units of signal generators of UAV radio transmitters.

PSD of phase noise of quartz reference generators is determined by the expression

$$S_{RG}(F) = \frac{10^{-7.82}}{F^3} + \frac{10^{-9.86}}{F^2} + \frac{10^{-12.7}}{F} + 10^{-15.8}; \quad (3)$$

the voltage-controlled oscillators (taking into account the noise of control circuit)

$$S_{VCO}(F)=\frac{10^{-13.3}}{F^{3}}\cdot\frac{f_0^{\ 2}}{Q^2}+\frac{10^{-16.7}}{F^{2}}\cdot\frac{f_0^{\ 2}}{Q^2}+\frac{10^{-13}}{F}+10^{-16.2}, \tag{4}$$

where the output frequency of the VCO; Q - the quality factor of the loaded resonator of VCO;

pulse-phase detectors based on their comparison frequency

$$S_{PPD}(F)=\frac{10^{-14}+10^{-28}f_{PD}^{\ 2}}{F^{3}}+10^{-16}+10^{-23}f_{PD}; \tag{5}$$

digital phase detectors, frequency dividers, and quadrature modulators as

$$S_{DPD}(F)=S_{Div}(F)=S_{QM}(F)=\frac{10^{-14.7}}{F}+10^{-16.5}; \tag{6}$$

frequency multipliers on bipolar transistors as

$$S_{FM\_BT}(F)=n1^2\cdot\frac{4kT}{P_S}\left[1+\frac{f_\alpha}{F}\right], \tag{7}$$

where $n1$ is the multiplication factor, k is the Boltzmann constant, T is temperature (T= 293 K), P_s is the input signal power (P_s = 1mW), and f_α is the boundary frequency of the flicker-noise predominance region in the transistor noise spectrum (f_α = 100 Hz).

and DDS as

$$S_{DDS}(F)=(K_{DDS})^2\left(\frac{10^{k_2}}{F^2}+\frac{10^{k_1}}{F}+10^{k_4}\right)+10^{k_3}+S_{кв}, \tag{8}$$

where k_1, k_2, k_3, k_4 are coefficients that determine the level of PSD of $1/F^2$ noise, $1/F$ noise, the natural noise component of the digital-to analog converter (DAC) input circuits and the natural noise component of the load resistance; $S_{quant}=2^{-2n\ -0.59}\left(\frac{f_{DDS}}{f_{REF}}\right)^2$ – PSD of phase noise due to quantization in the DAC.

Based on the presented equivalent scheme of the signal generator, as well as expressions (1)-(8), mathematical model of its noise characteristics is obtained:

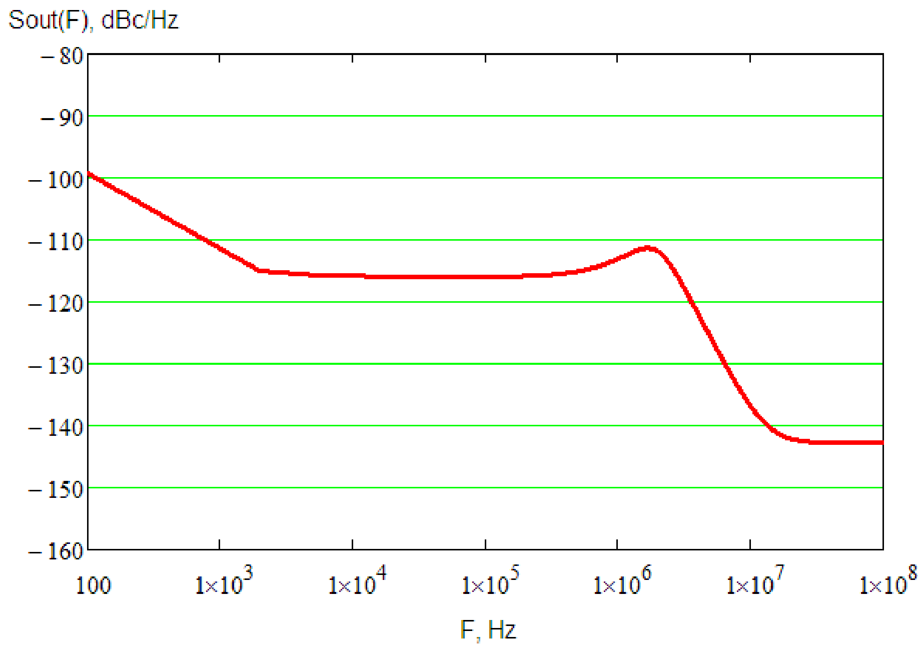
$$S_{out}(F)=(S_{RG}(F)+S_{PD}(F)+S_{div}(F))\cdot|H_{31}(F)|^2+S_{VCO}(F)|H_{32}(F)|^2+S_{RG}(F)\cdot 4n^2K_{DDS}^2+$$
$$+S_{FM}(F)\cdot 4K_{DDS}^2+S_{DDS}(F)\cdot 4+S_{QM}(F) \tag{9}$$

where $H_{31}(p)=\frac{H_1(p)N}{1+H_1(p)}$ is the transfer function of the PLL loop over external noise; $H_{32}(p)=\frac{1}{1+H_1(p)}$ - PLL transfer function for internal noise; $H_1(p)=\frac{M(p)K_{VCO}K_D}{pN}$ - transfer function of the open loop PLL.

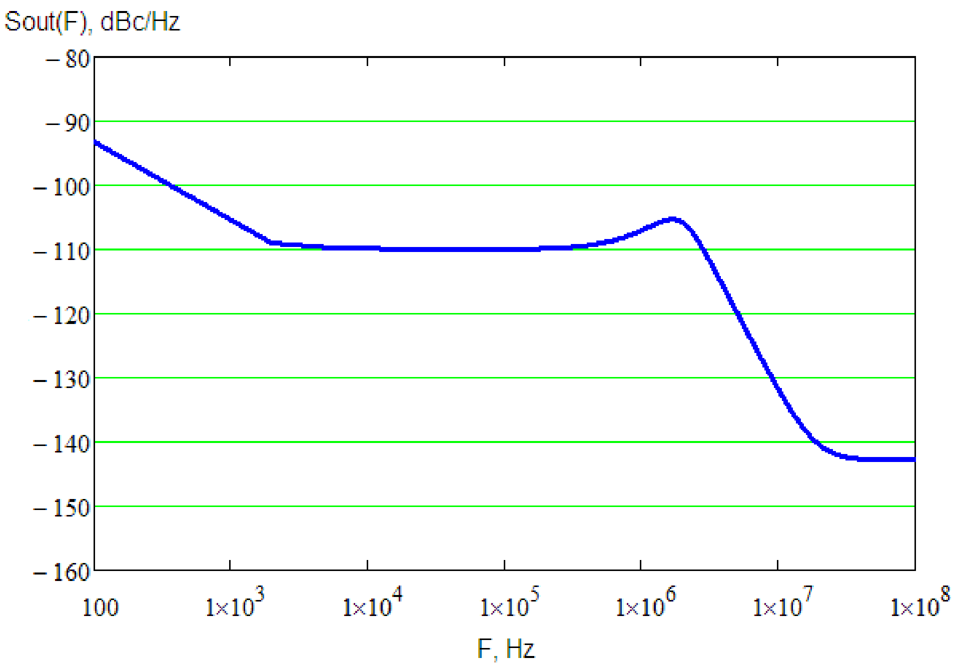
4. Modeling results of the noise characteristics of the signal generator of the UAV radio transmitter

A simulation of the noise characteristics of the proposed signal generator for a UAV radio transmitter was done. Simulation results are shown in Fig. 3. In this case, the frequency value of the reference quartz generator 20

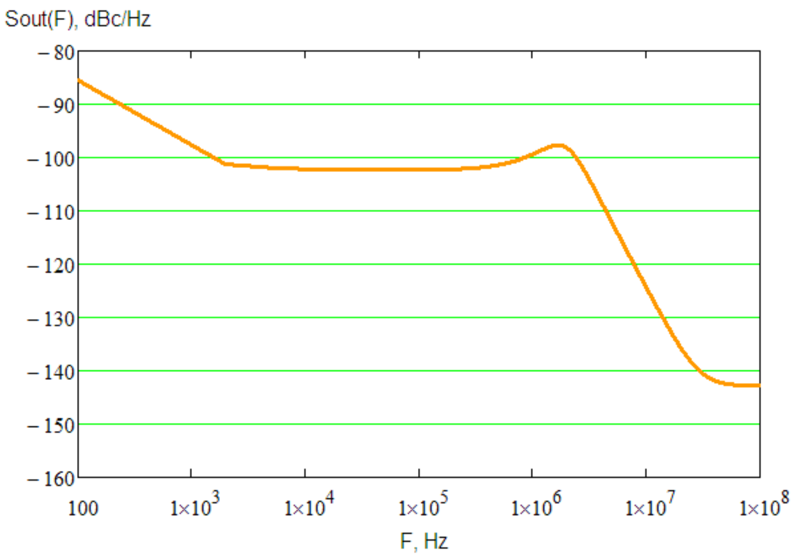
MHz was used, multiplied by a transistor frequency multiplier on three. Carrier frequencies of the generated signal (the VCO output signal of the PLL) are equal to 1200 MHz (Fig. 3A), 2400 MHz (Fig. 3B), 5800 MHz (Fig. 3C) and the transmission coefficient of the DDS K_{DDS}=0.25. The parameters of the AD9914 integral synthesizer with a 12-bit DAC were used for the modeling, and the parameters of the ADF5355 synthesizer with a steepness of the modulation characteristic K_{VCO} = 15 MHz/V, a steepness of the detector characteristic K_D = 1 V/rad and a cutoff frequency of the LPF f_{cut} = 10 MHz were used as a PLL loop.



A)



B)



C)

Fig. 3. PSD of phase noise of the UAV radio transmitter signal generator as function of frequency offset (*F*, Hz) for the carrier frequency 1200 MHz (A), 2400 MHz (B) and 5800 MHz (C)

The noise contribution of the components of the analyzed signal generator of the UAV radio transmitter for the carrier frequency of the generated signal 2400 MHz is shown in Fig. 4.

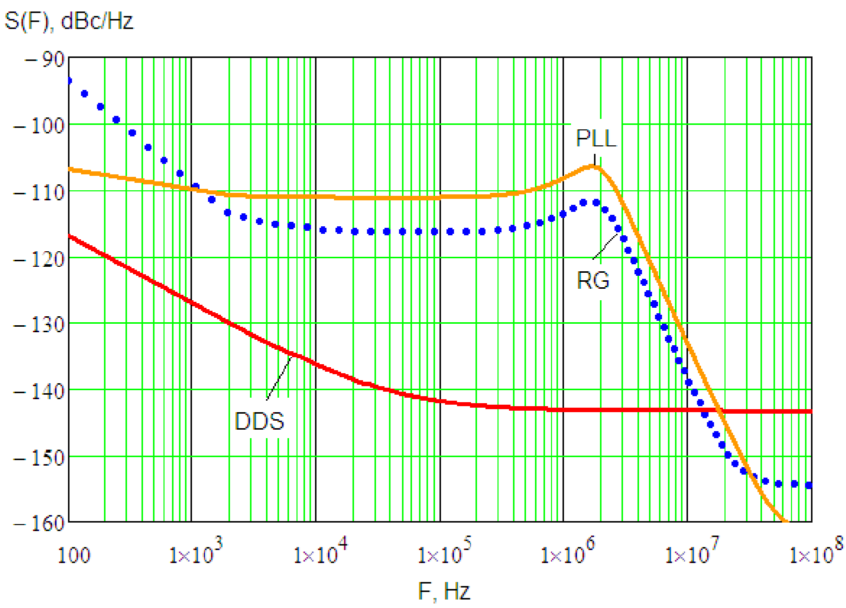


Fig. 4. Noise components of the UAV radio transmitter signal generator for the carrier frequency of the generated signal 2400 MHz

5. Conclusion

From the obtained results, it follows that for the analyzed signal generator circuit, phase noise at the offset of 1 kHz from the carrier oscillation, depending on the output frequency of the device, is characterized by a level of minus 100 - minus 115 dB/Hz, which is very typical for signal generation devices of this class. At the same time, with an increase in the frequency of the output signals of the generator, a proportional increase in its phase noise is observed.

The analysis of the noise contributions of the constituent units of the device allows to conclude that the resulting phase noise of all signal generator is determined by two components, reference (clock) oscillator (predominantly in the region of small offsets) and the elements of the loop PLL (predominantly in the rest of the frequency range until the cutoff frequency of its low-pass filter). A significant level of phase noise of the PLL loop in this case is due to large values of its multipliers (60 for the carrier frequency of 1200 MHz, 120 for 2400 MHz and 290 for 5800 MHz). It is caused by low comparison frequency of phase detector, which ideally should strive for the maximum possible value being realized by a specific chip (typically 100-125 MHz). This problem can be solved by placing an additional transistor frequency multiplier with a small multiplication factor between the reference oscillator of the signal generator and the phase detector of the PLL loop, or by using the signal from the output of FM2 to feed it to the input of FM1 in accordance with designations accepted in Fig. 1.

Further improvement of the spectral characteristics of signal generators of UAV radio transmitters can be achieved by reducing the level of discrete parasitic spectral components in the output spectrum of the DDS. An effective solution to this problem is to use an approach based on the principle of automatic compensation of phase distortions, which is discussed in detail in [26-31] and allows to reduce the level of discrete spurious spectral components in the output spectrum of the device by 10-15 dB, which is confirmed by numerous theoretical and experimental studies.

The results presented in this paper confirm the effectiveness of the proposed universal variant of signal generator as part of UAV radio transmitter, and the mathematical models developed for its analysis can serve as an effective tool for analyzing noise characteristics at the design stage of a specific signal generation device.

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