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Fluctuations of Transfer Factor of the Mixer Based on Schottky Diode

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***Abstract*—**Fluctuations of Schottky diode parameters in a structure of the mixer are investigated. These fluctuations are manifested in two ways. At the first, they lead to fluctuations in the transfer factor that is lead to the amplitude fluctuations in the signal of intermediate frequency. On the basis of the measurement data of 1/f noise of the diode at forward current, the estimation of a spectrum of relative fluctuations in transfer factor of the mixer is executed. Current dependence of the spectrum of relative fluctuations in transfer factor of the mixer and dependence of the spectrum of relative fluctuations in transfer factor of the mixer on the amplitude of the heterodyne signal are investigated. At the second, fluctuations in parameters of the diode lead to occurrence of 1/f noise in the output signal of the mixer. This noise limits the sensitivity of the mixer to the value of received signal.

***Keywords*—**Current-voltage characteristic, fluctuations, mixer, Schottky diode, 1/f noise.

I. Introduction

SCHOTTKY barrier diodes [1]-[3] are important devices in very high frequency receivers, microwave detectors and mixers [4]-[14] where noise is often a limiting factor of the overall system performance. Schottky barrier diodes have been widely studied and many attempts have been made to understand the fluctuation mechanism in such diodes [15]-[35]. However, questions of the analytical description of 1/f noise of these diodes working in structure of the mixer practically are not investigated in the literature. This problem is solved in the present work. The transfer factor of the mixer depends, as known, from parameters of a nonlinear element and amplitude of heterodyne signal. Parameters of nonlinear element (in our case of Schottky diode) can be subjected to fluctuations, that lead to fluctuations of transfer factor of the mixer. In the present work, the problem of an estimation of a spectrum of fluctuations of transfer factor of the mixer is investigated. These fluctuations are caused by 1/f noise of Schottky diode. On the basis of the measurement data of 1/f noise of the diode on a forward current, the estimation of the spectrum of relative fluctuations of transfer factor of the mixer is executed. Current dependence of the spectrum of relative fluctuations of transfer factor of the mixer and dependence of the spectrum of relative fluctuations of transfer factor of the mixer on the amplitude of a heterodyne signal is investigated.

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II. Fluctuations of Transfer Factor of the Mixer Based on Schottky Diode

Equivalent circuit diagram of the mixer is shown in Fig. 1 [35], [36].

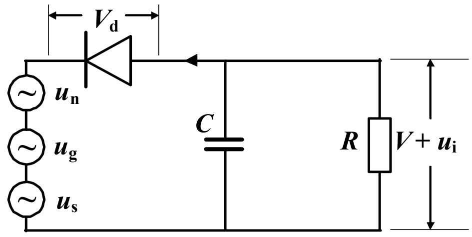

Fig. 1 Equivalent circuit diagram of the mixer

In Fig. 1 indicated: $u_g=V_g\cos(\omega_g t+\varphi_g)$ is the heterodyne signal and $u_s=V_s\cos(\omega_s t+\varphi_s)$ is the input signal, $V_s << V_g$. Signal of intermediate frequency is $u_i=V_i\cos(\omega_i t+\varphi_i)$ with frequency $\omega_i= |\omega_g - \omega_s|$.

Absolute value of transfer factor of the mixer is:

$$K = V_i / V_s \, . \tag{1}$$

We will consider the output voltage of the mixer $V_0 + u_i$, here V_0 – direct voltage.

Parameters of Schottky diode can be subjected to fluctuations. These fluctuations, firstly, lead to fluctuations of transfer factor and are transformed into fluctuations of the signal at intermediate frequency $K\cdot(1+\delta K)=V_i\cdot(1+m)/V_s$. Here δK – relative fluctuations of transfer factor of the mixer and m – relative fluctuations of the amplitude. Secondly, the 1/f noise of the diode $u_n(t)$ is appeared, which is shown as $v_n(t)$ in the output signal of the mixer. Thus, the 1/f noise of the diode and noise in the output signal of the mixer are connected by relation $v_n = [R/(R+R_d)]\cdot u_n$. Here R_d is differential resistance of the diode. Output voltage (in Fig. 1) $V = V_0 + v_n$ consists of the "constant" component, described by noiseless value V_0, and voltage noise $v_n = v_n(t)$.

Measurements have shown that in current-voltage characteristics (I-V characteristics) of the investigated diodes alongside with thermionic component (which prevails at rather large currents) additional current components are shown. In [37], additional current components in Schottky diodes also have been found. One component has nearly ohmic character (leakage); it is poorly shown at small currents. The second component is caused by the mechanism of thermionic-field emission of electrons through the top of a barrier on the metal-semiconductor border [38]. In the difference with work [1] where thermionic emission was considered as the basic component, in the present work we consider the thermionic-field emission as the basic component. It is caused by the fact that thermionic component prevails in I-V characteristic at voltages and currents more than 0.7 V and 10^{-3} A, accordingly. The thermionic-field component prevails in a range of voltages 0.1 - 0.7 V and currents 10^{-5} - 10^{-3} A. At voltages less than 0.1 V and currents less than 10^{-5} A linear leakage becomes visible in I-V characteristic. We investigate the nonlinear operating mode of the device, so the range less than 0.1 V and less than 10^{-5} A is not analyzed here. Thus, in [1], the case of relatively large currents and voltages was considered, and in the present work – the case of relatively small ones.

If the current transport is controlled by the thermionic-field emission, the relation between current and voltage can be expressed (for rather high forward bias) as [38]:

$$I_d = I_s \cdot \exp(V_d / E_0) \tag{2}$$

with I_s – characteristic current of thermionic-field emission component and

$$E_0 = E_{00} \cdot \mathrm{cth}(qE_{00}/kT), \tag{3}$$

where E_{00} is the characteristic potential, which is related to the transmission probability of the carrier through the barrier for n-type semiconductor:

$$E_{00} = \frac{\hbar}{2}\sqrt{\frac{N_D}{\varepsilon_s \varepsilon_0 m^*}} \tag{4}$$

here $\hbar$ is the Planck constant; $m^*=m_r m_0$ – effective mass of electron in the semiconductor, m_r is the relative effective mass of an electron, m_0 – free electron mass; ε_s – relative permittivity; ε_0 – vacuum permittivity (electric constant or absolute dielectric permittivity); N_D – concentration of ionized donor atoms.

For a case of the p–type semiconductor, N_D is replaced on N_A – concentration of ionized acceptors in the semiconductor. In this case, on the basis of [35], [36], we find the absolute value of transfer factor of the mixer:

$$K = \frac{V_{\mathrm{i}}}{V_{\mathrm{s}}} = \frac{I_{\mathrm{d}0} R}{E_0 + I_{\mathrm{d}0} R} \mu(\xi). \tag{5}$$

Here $I_{\mathrm{d}0}$ – direct current through the diode, $\mu(\xi) = I_1(\xi)/I_0(\xi)$ – the ratio of modified Bessel functions of zero and first orders $I_0(\xi)$, $I_1(\xi)$, and $\xi = V_{\mathrm{g}}/E_0$ – dimensionless heterodyne amplitude. Except area of very small current the direct current $I_{\mathrm{d}0}$ through the diode is defined by

$$I_{\mathrm{d}0} = I_{\mathrm{s}}\left[I_0(\xi)\exp\left(-\frac{I_{\mathrm{d}0}R}{E_0}\right)\right]. \tag{6}$$

Taking to account fluctuations, we transform (2) as:

$$I_{\mathrm{d}} + i_{\mathrm{n}} = I_{\mathrm{s}} \cdot \exp\left(\frac{V_{\mathrm{d}} + u_{\mathrm{n}}}{E_0}\right). \tag{7}$$

Equation (5) is transformed as

$$K \cdot (1 + \delta K) = \frac{V_{\mathrm{i}} \cdot (1+m)}{V_{\mathrm{s}}} = \frac{(I_{\mathrm{d}0} + i_{\mathrm{n}})R}{E_0 + (I_{\mathrm{d}0} + i_{\mathrm{n}})R}\mu(\xi). \tag{8}$$

Here i_{n} is noise in the current caused by 1/f noise of the diode. It is considered, that relative noise in the current coincides with relative noise in the voltage on resistor, $i_{\mathrm{n}}/I_{\mathrm{d}0} = v_{\mathrm{n}}/V_0$.

From (8), we can conclude that the value of the relative fluctuations in transfer factor coincides with value of relative fluctuations in amplitude of the output signal, caused by noise of the diode.

It is possible to find relation of relative fluctuations in transfer factor of the mixer with relative fluctuations in voltage of output signal of the mixer from (8).

Consider now relative fluctuations in transfer factor of the mixer δK ($i_{\mathrm{n}}/I_{\mathrm{d}0} \ll 1$):

$$\delta K = \left[1 + \frac{I_{\mathrm{d}0}R}{E_0}\right]^{-1} \frac{i_n}{I_{\mathrm{d}0}} = \left[1 + \frac{I_{\mathrm{d}0}R}{E_0}\right]^{-1} \frac{v_n}{V_0}. \tag{9}$$

Note: We can calculate relative fluctuations in transfer factor of the mixer by another way:

$$\delta K = \frac{\mathrm{d}K}{K} = \frac{1}{K}\frac{\partial K}{\partial I_{\mathrm{d}0}} \mathrm{d}I_{\mathrm{d}0}. \tag{10}$$

From (9) it is possible to get the following equation for the spectrum:

$$\left\langle \delta K^2 \right\rangle_f = \left[1 + \frac{I_{\mathrm{d}0}R}{E_0}\right]^{-2} \frac{\left\langle v_{\mathrm{n}}^2 \right\rangle_f}{V_0^2}. \tag{11}$$

This equation defines spectrum of relative fluctuations in transfer factor of the mixer based on Schottky diode.

For estimations, we have chosen parameters of Schottky diodes investigated in [15], where n^+–GaAs substrate was used.

Investigations of the 1/f noise of Schottky diodes [15], have shown, that at the fixed current through the diode:

$$\left\langle u_n^2 \right\rangle_f = \frac{A}{f^\gamma}, \tag{12}$$

here γ depends on the diode sample, and have magnitudes close to unit. Value A depends on a type of the diode and on the current through the diode. It is necessary to note that expression of type (12) is true not only for Schottky diodes, but also for other types of diodes, see, for example, [39], [40].

Using relation between v_n and u_n we can find the spectrum:

$$< v_n^2 >_f = \left[\frac{R}{R+R_d}\right]^2 < u_n^2 >_f \qquad (13)$$

for typical value γ=1 and direct current through the diode, equal I_{d0}= 1 mA:

$$\frac{\left\langle v_n^2\right\rangle_f}{V_0^2} \approx \frac{\left(10^{-15}-10^{-14}\right)}{f}\left[\frac{1}{\text{Hz}}\right]. \qquad (14)$$

For estimation of spectrum of relative fluctuations in transfer factor of the mixer based on Schottky diode we use typical values of parameters of the diode [15] I_s=5·10^{-5} A, E_0=0.3 V, R =9 Ohm and I_{d0}= 1 mA. Thus, we have $\left\langle \delta K^2\right\rangle_f = 0.94\cdot\left\langle v_n^2\right\rangle_f \big/ V_0^2$. Using a little bit overestimated data, it is possible to consider that at I_{d0} = 1 mA for real mixers, based on Schottky diodes, the spectrum of relative fluctuations in transfer factor can be estimated as:

$$\left\langle \delta K^2\right\rangle_f = \frac{\left(10^{-15}-10^{-14}\right)}{f}\left[\frac{1}{\text{Hz}}\right] \qquad (15)$$

for frequencies f=1 Hz – 20 kHz.

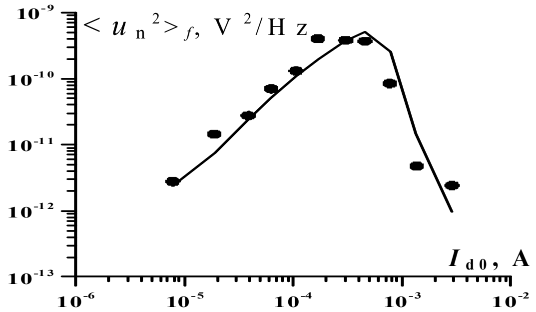

Fig. 2 Dependence of the voltage noise spectrum on the direct current through the diode at frequency 10Hz

Now we can calculate spectrum of relative fluctuations in transfer factor of the mixer based on Schottky diode versus direct current through the diode. At first, we consider dependence of spectrum of voltage relative fluctuations of Schottky diode on direct current (see Fig. 2).

Experimental data and 1/f noise in the thermionic-field emission current are shown in Fig. 2 by dots and solid line accordingly (frequency 10Hz).

A model is presented in work [38] in detail. The diodes considered here, in difference with the diodes investigated in [38], have SiO_2 layer. As calculations have shown, the thermionic-field emission component only can be detected in the current dependence of the spectrum presented in Fig. 2, in difference with diodes from work [38], where the linear (ohmic) leakage was visible.

Now, using (11), it is possible to calculate dependence $\left\langle \delta K^2\right\rangle_f$ on I_{d0} (see Fig. 3).

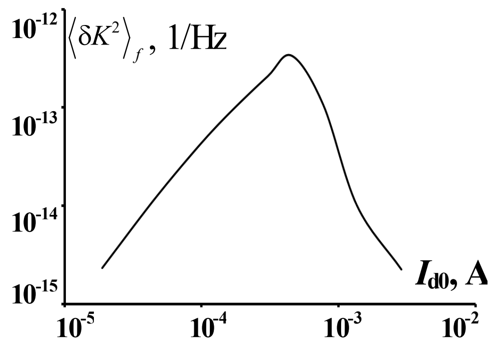

Fig. 3 Dependence of the spectrum of relative fluctuations in transfer factor of the mixer on the direct current through the diode

Using dependence (6) of direct current I_{d0} on heterodyne amplitude, it is possible to calculate dependence $\left\langle \delta K^2\right\rangle_f$ on V_g. In this case the spectrum of relative fluctuations in transfer factor of the mixer coincides with the spectrum of amplitude fluctuations in output signal, caused by noise of the diode, $\left\langle m^2\right\rangle_f = \left\langle \delta K^2\right\rangle_f$ (see Fig. 4).

Using (6), it is possible to find the dependence $\left\langle \delta K^2\right\rangle_f$ from V_g (see Fig. 4). This dependence is calculated numerically in software MATLAB 6.5.

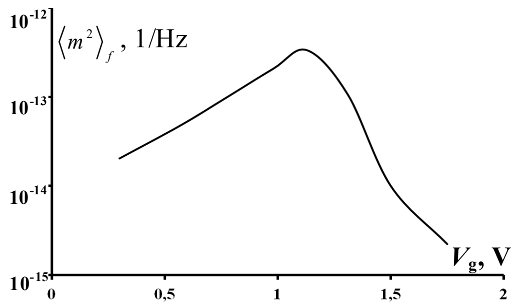

Fig. 4 Dependence of the spectrum of relative fluctuations in amplitude of the output signal on the heterodyne voltage

III. Conclusion

The analysis of fluctuations in the transfer factor of the mixer based on Schottky diode was provided. That is with the increase of amplitude of heterodyne signal V_g up to 1 V the magnitude of the spectrum of relative fluctuations of transfer factor of the mixer is slowly increased and is characterized by value 2×10^{-13} Hz^{-1}. The further increase of amplitude of heterodyne signal V_g leads to fast decrease of the spectrum of relative fluctuations in transfer factor. For example, at V_g =1.5 V it is of the order 10^{-14} Hz^{-1}.

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