Application of Ultrafast Schottky Diodes to High Megahertz Chaotic Oscillators

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The considered chaotic oscillator consists of an amplifier, 2nd order LC resonator, Schottky diode and an extra capacitor in parallel to the diode. The diode plays the role of a nonlinear device. Chaotic oscillations are demonstrated numerically and experimentally at low as well as at high megahertz frequencies, up to 250 MHz.

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1. Introduction

The Schottky-barrier diodes are commonly classified as low-noise high-speed semiconductor devices for high frequency and microwave applications. When reverse-biased at the breakdown voltages they can be employed as noise sources characterized by an effective noise temperature from 10^3 K to 10^4 K [1].

In the present paper we describe high-power noise generator with a Schottky diode. Actually it is a dynamical noise (chaos) generator similar to the tunnel diode oscillator driven by external sinusoidal voltage [2, 3]. The main shortcoming of the externally driven (non-autonomous) systems is that sharp peaks do appear in the power spectra at the drive frequency and its higher harmonics. In contrast, the dynamical noise generator suggested in this paper is an autonomous one, providing essentially smoother power spectra. Two experimental prototypes of the oscillator operating at different fundamental frequencies $f^* = 1/2\pi\sqrt{LC}$ have been investigated. The first one has been set at low megahertz frequency ($f^* \approx 1$ MHz), meanwhile the second one has been tuned to operate at high megahertz frequency ($f^* \approx 100$ MHz).

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2. Structure of the dynamical noise generator

A simplified diagram of the dynamical noise generator is shown in Fig. 1. A series 2nd-order LC resonator and a non-inverting amplifier are common building
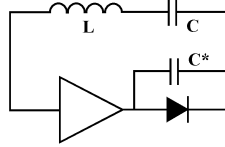

Fig. 1. Circuit diagram of chaotic oscillator with the Schottky diode. DC bias circuit is not shown for simplicity.

blocks of a classical sinusoidal oscillator. However, additional elements, namely the Schottky-barrier diode and an extra capacitor C^* are inserted in the positive feedback loop. The diode plays the role of a nonlinear device, while the capacitor C^* acts as an extra energy storage (inertial) element. The overall system becomes a *nonlinear* dynamical system with *three* degrees of freedom, thus it is a potentially chaotic oscillator [4].

3. Equations and numerical results

Dynamics of the oscillator is given by the following rate equations:

$$C\dot{V}_C = I_L,$$

$$L\dot{I}_L = (kR_{\text{in}} - R_{\text{in}} - R_{\text{out}})I_L - V_C - V_d,$$

$$C^*\dot{V}_d = I_0 + I_L - I_{\text{S}}\left(\exp\frac{qV_d}{k_{\text{B}}T} - 1\right). \tag{1}$$

Here V_C and I_L is the voltage across the capacitor and the current through the inductor of the LC resonator, respectively; V_d, I_0, and I_{S} is the voltage, the dc bias current, and the reverse saturation current of the Schottky diode, respectively; k, R_{in}, and R_{out} is the gain, the input and the output resistance of the amplifier, respectively. The exponential term in the third equation represents the current–voltage characteristic of the diode. By introducing the dimensionless variables and parameters

$$x = \frac{V_C}{V_T}, \qquad y = \frac{\rho I_L}{V_T}, \qquad z = \frac{V_d}{V_T}, \qquad t' = \frac{t}{\tau}, \tag{2}$$

$$V_T = \frac{k_{\text{B}}T}{q}, \qquad \rho = \sqrt{\frac{L}{C}}, \qquad \tau = \sqrt{LC},$$

$$a = \frac{R_{\text{n}}}{\rho}(k-1) - \frac{R_{\text{out}}}{\rho}, \qquad b = \frac{\rho I_0}{V_T}, \qquad c = \frac{\rho I_{\text{S}}}{V_T}, \qquad \varepsilon = \frac{C^*}{C}, \tag{3}$$

the following set of equations convenient for numerical integration is obtained:

$$\dot{x} = y,$$

$$\dot{y} = ay - x - z,$$

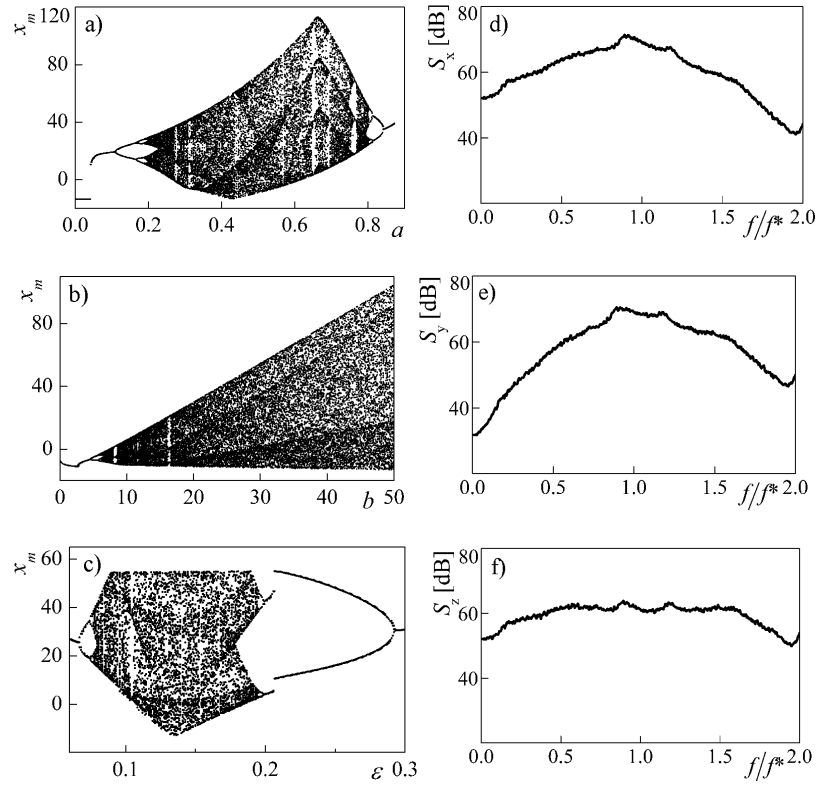$$\varepsilon\dot{z} = b + y - c(\exp z - 1). \tag{4}$$

Fig. 2. Left part: bifurcation diagrams, i.e. local maxima x_{m} of variable $x(t)$ versus control parameters a, b, and ε at $c = 4 \times 10^{-5}$: (a) $b = 30$, $\varepsilon = 0.13$; (b) $a = 0.4$, $\varepsilon = 0.13$; (c) $a = 0.4$, $b = 30$. Right part: power spectra ($f^* = 1/2\pi\tau$) calculated from variables x, y, and z at $a = 0.4$, $b = 40$, $\varepsilon = 0.13$.

The oscillator exhibits period-doubling route to chaos, narrow periodic windows in the chaotic domains, and reverse bifurcations as illustrated with the bifurcation diagrams in Fig. 2. Several power spectra are also presented.

4. Experimental results

Experiments were carried out using silicon Schottky diodes, namely BAT41 or BAT43 (recovery time $\tau_{\mathrm{rec}} = 5$ ns, junction capacitance $C_d = 2$ pF) at low
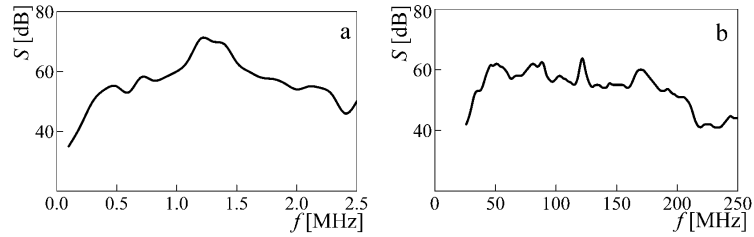
Fig. 3. Power spectra taken at the output ($V_{\text{out}} = kR_{\text{in}}I_L \propto y$) of the amplifier for different diodes. (a) BAT41, $I_0 \approx 7$ mA, $L = 8$ μH, $C = 2.7$ nF, $C^* = 360$ pF, $k \approx 2$, $R_{\text{in}} = 50$ Ω, $R_{\text{out}} \approx 0$. Resolution $\Delta f = 70$ kHz. (b) HSMS8101, $I_0 \approx 3$ mA, $L = 100$ nH, $C = 22$ pF, $C^* = 3.3$ pF, $k \approx 3$, $R_{\text{in}} = R_{\text{out}} = 50$ Ω. Resolution $\Delta f = 120$ kHz. The level of 0 dB corresponds to effective noise temperature of 10^5 K.

megahertz frequency and microwave diode HSMS8101 ($\tau_{\text{rec}} = 25$ ps, $C_d = 0.3$ pF) at high megahertz frequency. The results are presented in Fig. 3 as broadband continuous power spectra. These spectra are in a qualitative agreement with the numerical ones.

5. Conclusions

Schottky diodes have been demonstrated to be applicable to high megahertz frequency chaotic oscillators. The effective noise temperature in the frequency range from 50 to 200 MHz is about 10^{11} K, i.e. 7 orders higher than in [1]. In addition, the power spectrum is essentially smoother than of the tunnel diode based oscillator [2, 3]. Schottky diode chaotic oscillators potentially can be set to gigahertz frequencies by removing the capacitor C^* (its role plays the junction capacitance C_d) and setting the LC resonator elements at $L \leq 10$ nH and $C \leq 2$ pF.

Acknowledgment

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