Collective pulse-density modulation with neuromorphic single-electron circuits

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We designed a neuromorphic single-electron oscillator network as an inhibitory neural network model that performs pulse-density modulation (PDM) [1]. The use of single-electron oscillator networks has been proposed for implementing functions of neural networks [2] and reaction-diffusion systems [3]. Single-electron circuits are being studied for use in next-generation LSI devices. We designed a single-electron oscillator network for performing PDM and simulated its operation on a computer to demonstrate it could perform PDM.

In Ref. [1], the network consists of N integrate-and-fire neurons (IFNs) with all-to-all inhibitory connections. A common analog input is given to all the IFNs, and a 1-bit digital signal is output as the sum of firing events of the IFNs. Static and dynamic noise is introduced into the analog input and the reset potential of the IFNs after each firing, respectively. Since the wiring complexity of the network; i.e., $O(N^2)$ in Ref. [1], can be simplified to $O(N)$ by introducing a global inhibitor [4], we designed the network circuit as shown in Fig. 1. In the circuit, we used single-electron oscillators as IFNs and numerical calculations to represent output signals of a global inhibitor (G). The single-electron oscillator consisted of a tunneling junction (C_j), a capacitor for inhibiting signals from G (C), and a bias register (R) that was connected to a bias voltage source (V_d). The static and dynamic noises were introduced to the circuit as tunneling rates of the oscillators and thermal noise, respectively. We tested the network using computer simulations. Figure 2 shows example results (Circuit parameters: N = 10, C_j = 10 aF, a conductance of a tunneling junction = 1 μS, R = 1 GΩ, C = 2 aF, V_d = 6.75-6.78 mV, T = 0.5 K). Inter-spike-intervals (ISIs) of the output spike trains (the sum of tunneling events of N oscillators) looked random when the oscillators were uncoupled. In contrast, the ISIs were almost uniform when the oscillators were coupled through the global inhibitor. Figure 3 shows the number of output spikes against ISIs for uncoupled and coupled network circuits. According to Mar et al. [1], the coupled network produces a Gaussian-like distribution of ISIs, while the uncoupled one has a broader distribution. Simulation results indicate that the single-electron network had a PDM function because of the following three points, a time for charging of the node voltage to an initial value after the voltage was changed suddenly by firing (electron tunneling) (τ), noises, and a property of a global inhibitor. Here, τ was about 20-50 ns according to the simulation. The ISIs scattered because of the thermal noise and tunneling probability of the oscillator. The outputs of the global inhibitor are given by $V_{out} = A\int(\Sigma V_{node\,i} - N\,V_{out})dt$, where A is a constant and $V_{node\,i}$ is the i-th oscillator's node voltage; i.e., a change in the node voltage at the i-th oscillator inhibits firing at the others through G during charging of the oscillator. Inhibitory time should thus be simply τ/N. After this inhibition has finished, the next firing can occur; i.e., the ISIs for a coupled network is thus τ/N. We are currently testing the effects of noise shaping [1] on an oscillator network. For the noise shaping functions, the network should have a winner-share-all (WSA) function [5] or a stochastic resonance (SR) function [6] so that it can operate as a PDM circuit in a low-temperature environment (T ~ 1 K). We thus plan to modify the circuit that includes WSA or SR functions as a future work.

References

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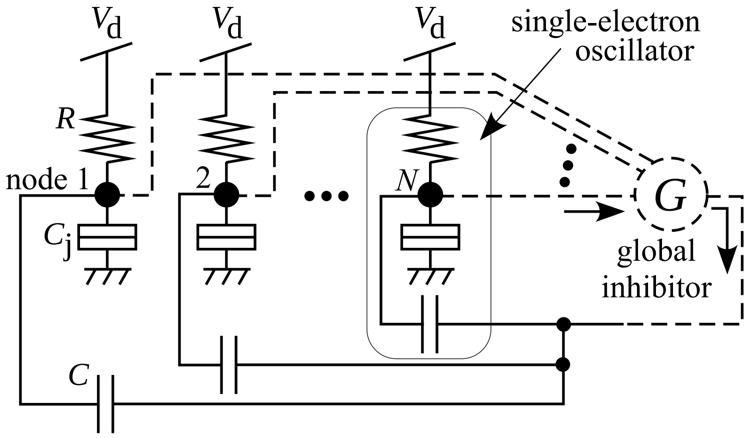

Fig. 1. Circuit configuration. Dashed lines represent simplified circuit.

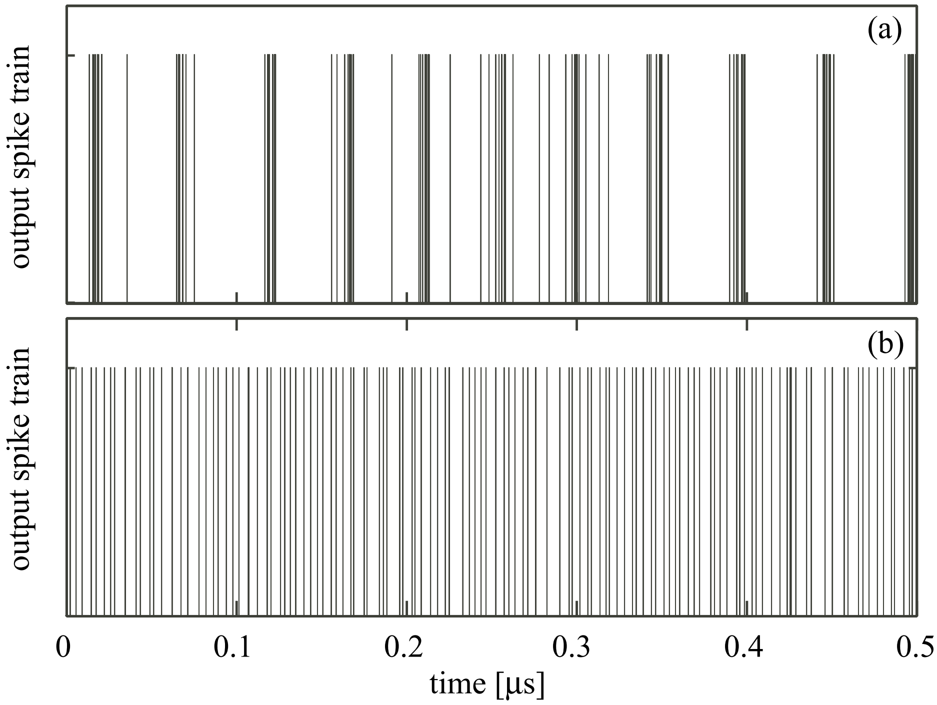

Fig. 2. Output spikes of (a) uncoupled and (b) coupled network circuit. (T = 0.5 K)

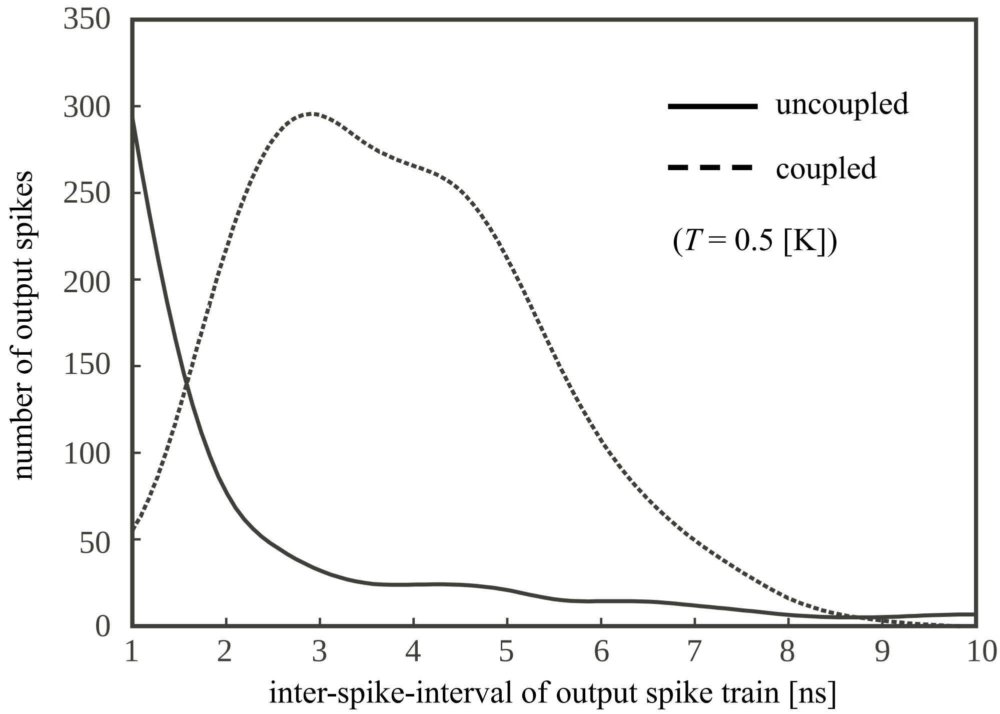

Fig. 3. Histogram of inter-spike-intervals. (Same simulation as Fig. 2. except operating time = 0-10 [μs].)