Synchronization Properties of Pulse-Coupled Resonate-and-Fire Neuron Circuits and Their Application

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Introduction: Recent advances in neuroscience suggest that spiking neurons in cortical area are classified into two categories: integrators and resonators [1]. These neurons are different in the sensitivity to the timing of stimulus, and therefore show different synchronization properties in pulse-coupled systems. It is interested that the distribution of such neurons are layer-specific and depends on whether excitatory or inhibitory from a point of view of information processing in the cortical area.

Functional networks of silicon spiking neurons have been progressing in the field of neuromorphic engineering, most of which are constructed from electronic analogues of integrators, such as the integrate-and-fire neuron (IFN) circuit. In spite of possible contributions, it has been rarely considered to implement an analog integrated circuit for resonators into the silicon spiking neural networks.

In this paper, we will first describe an analog integrated circuit for a resonate-and-fire neuron (RFN) model, which is the simplest resonator proposed by Izhikevich [1]. We will then describe curious synchronization phenomena in two pulse-coupled RFN circuits. We will further describe synchronization properties of a system of globally coupled RFN circuits with inhibitory coupling and its application for neuromorphic noise shaping. We will finally discuss about complementary roles of the RFN circuits in the IFN circuits in very large-scale integration (VLSI) of the silicon spiking neural networks.

Analog VLSI Implementation of Resonate-and-Fire Neuron Model: We have designed an analog integrated circuit implementing the RFN model [4]. The RFN model has second-order membrane dynamics, and thus it exhibits a damped subthreshold oscillation of membrane potential, resulting in coincidence detection, frequency preference, and post-inihibitory rebound [1]. We implemented such dynamical behavior into an analog integrated circuit using a standard CMOS technology. As a result, our circuit can act as a coincidence detector, and at the same time as a band-pass filter for a sequence of pulse inputs [4].

Burst Synchronization in Two Pulsed-Coupled RFN Circuits: We have investigated synchronization states in two pulse-coupled RFN circuits [5]. So far the existence of in phase and anti phase states in two pulse-coupled RFN model has been reported [2]. However, the influence of after-spike reset on the synchronization states were not considered. We found burst synchronization in out of phase and bifurcation phenomena depending on reset value [5]. We analyzed the stability of such burst synchronization in detail. The results confirmed that the burst synchronization were robust against noise and insensitive to the influence of device deviation, and pulse duration may enhance the stability of the burst synchronization.

Neuromorphic Noise Shaping in Globally Coupled RFN Circuits: Biological sensory systems may utilize noise shaping, which is a circuit principle originally established for improving the dynamic range (DR) and the signal-to-noise ratio (SNR) in electronic AD converters, as well as in population rate coding for noisy sensory signals [6]. Mar et al. have shown that a system of coupled IFNs with global inhibition can perform neuromorphic noise shaping in a population rate coding [6]. Such a network has previously been implemented as an analog subthreshold CMOS circuit for ultralow-power AD converters [7]. The performance of the neuromorphic noise shaping depends on the correlation between the elements of the network, and the correlation property of globally inhibitory coupled RFNs is superior to that of the coupled IFNs [3]. Based on this, we verified the performance of the noise shaping in the coupled RFN circuits with SPICE simulations. The results showed that the correlation between the inter-spike interval (ISI) of the RFN circuits increased with the number of the elements, and the normalized noise spectrum of ISI of the system was reduced.

Summary: Synchronization properties of pulse-coupled RFN circuits we have considered here are very different from that of IFN circuits used in the previous works. Such differences may contribute to play complementary roles in information processing in neuromrophic VLSI systems.

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