International Congress Series 1291 (2006) 221–224

www.ics-elsevier.com

Single-flux-quantum circuits for spiking neuron devices

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Abstract. Single-flux-quantum (SFQ) circuits can be used for making spiking neuron devices, which are useful elements for constructing intelligent, brain-like computers. The device we propose is based on the integrate-and-fire neuron model and uses an SFQ pulse as an action signal or a spike of neurons. Computer simulation has shown that the device successfully operated with a short delay of 100 ps or less. It is the highest-speed neuron device ever reported.

Keywords: Single-flux-quantum; Spiking neuron; Integrate-and-fire model

1. Introduction

A promising area of research in single-flux-quantum (SFQ) electronics is the development of systems that imitate the function of biological neuron systems. To proceed toward this goal, we propose a spiking neuron device consisting of SFQ circuits.

Brain-like computing has attracted considerable attention in recent years. To embody brain-like computing, we must first develop the way of constructing electrical analogues of biological neuron systems. For this purpose, several models to describe the dynamics of neurons have been proposed, though the study of neurons is still at an early stage and has yet to provide a complete picture of neurons. Among these models, the integrate-and-fire neuron (IFN) model is most used for its simplicity to analyze and simulate the behavior of neuron systems. With the IFN model, several electrical neuron systems have been produced experimentally using CMOS circuit technology [1].

In this paper, we propose an SFQ circuit that can implement the IFN model. Unlike CMOS circuits, a medium for signals in SFQ circuit is a pulse of a fluxoid quantum and, therefore, SFQ circuits will be able to imitate the operation of neurons more precisely. In addition, SFQ circuits are superior in speed capability (3 or 4 orders of magnitude faster) than CMOS circuits, so they will provide the highest-speed neuron devices ever reported.

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doi:10.1016/j.ics.2006.02.005

2. IFN model

A biological neuron can be divided into three functionally distinct parts called dendrites, soma and axon. The dendrites play the role of "input terminals" that collect signals from other neurons and transmits the signals to the soma. The soma is a "central processing unit" that performs a nonlinear threshold processing step. If the total inputs reach a certain threshold, the neuron "fires" and outputs a signal. The output signal is taken over by the "output terminal", the axon, which delivers the signal to other neurons. The signal in neuron is a short pulse of cell membrane potential called the action potential. It is often called the spike and the neuron is often called the spiking neuron. The dynamics of spiking neurons can be expressed by simultaneous differential equations such as Hodgkin-Huxley equations. However, these equations are intrinsically complex and therefore unsuitable for analyzing network systems with many neurons. For this reasons, simple phenomenological models, especially the IFN model, are popularly used for studies of network dynamics. The IFN model is defined as follows [2]: A neuron has a single variable $u(t)$, the membrane potential, that is given by

$$\frac{\mathrm{d}u(t)}{\mathrm{d}t} = I(t) - \frac{u(t)}{\tau}, \ldots \qquad (1)$$

where $I(t)$ is the sum of inputs for the neuron, τ is the time constant of the neuron and t is time. The neuron outputs an impulse (δ-function spike) when $u(t)$ reaches a certain threshold value. After producing the output, the neuron resets $u(t)$ to 0 to initialize itself. In the next section, we propose a SFQ circuit that imitates the dynamics of the IFN model.

3. Circuit configuration

The spiking neuron device we propose uses an SFQ pulse as an impulse signal. It consists of three SFQ subcircuits, i.e., an input subcircuit, a leaky integrator subcircuit and an output subcircuit. They correspond to dendrites, soma and axon of biological neurons. The input subcircuit is a simple confluence buffer that collects SFQ pulses from other neuron devices and sends the pulses to the leaky integrator subcircuits. The leaky integrator subcircuit is the key component of our device. It accepts and stores input fluxoid quanta and produces an output SFQ pulse when the number of stored fluxoid quanta exceeds a certain threshold. The output subcircuit sends the output SFQ pulse to other neurons and simultaneously produces resetting pulses for the leaky integrator. In constructing the neuron device, we used elementary SFQ circuit components given in [3].

3.1. Leaky integrator subcircuit

Fig. 1(a) shows the leaky integrator subcircuit. The leaky integrator consists of Josephson memory loops. Loop J_1–L_1–R_1–J_0 has a damping resistor R_1. Each Josephson junction from J_1 to J_N is biased with a dc bias current (denoted by idc). Junction J_0 is designed so that its critical current will be larger than that of other junctions and it is not biased. The circuit receives SFQ pulses from the input subcircuit, transmits the fluxoid quanta rightward and stores the fluxoid quanta in its loops. The stored fluxoid quantum in the right end loop (J_1–L_1–R_1–J_0) fades away with a certain time constant because of damping resistor R_1. We define the total current ("current in L_1"+"current in L_2"+. . .+"current in L_N") in the loops as the internal state of the neuron device that