Real-time memory on an excitable field

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Recently, we proposed a novel method for computing logic operations based on the time-sequential information in a geometrically arranged excitable field. As an extension of this study, in the present article we describe a strategy for creating real-time memory. Using a numerical simulation, we show that input pulse trains can be stored as a sequence of rotating traveling waves in a circular excitable field, by using its characteristics as a diode due to spatially asymmetric arrangement. Furthermore, through an experiment on an excitable chemical reaction, we demonstrate that this real-time memory actually works in the real world.

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I. INTRODUCTION

One of the essential aspects of modern digital computers is their step-wise operation using a CPU equipped with a ruling clock. Improvements in this step-wise operation, with regard to speed and reliability, have made digital computers indispensable in modern human society. However, despite advances in digital computers, the sequential step-wise operation inevitably causes a serious bottleneck in performing simultaneous computations using large data sets. To overcome such a bottleneck, various approaches to parallel computation have been proposed. Most previous studies on parallel computation seem to have focused on the problem of how to connect multiple unit computers in an effective manner [1]. On the other hand, parallel computation occurs routinely in living organisms without any ruling CPU or ruling clock. Thus, an investigation of parallel computation that mimics the essentials of computation in living organisms may be fruitful. With regard to the information processing in biology, there are an increasing number of observations of an autowave, or traveling wave, in living organisms, not only in nerve cells but also in a wide variety of cellular systems [2–5].

Recently, it has been reported, in both a simulation and an actual experiment on an excitable system, that the characteristics of a diode appear in an asymmetric junction between neighboring excitable fields [6]. With a diode, a traveling wave is transmitted in only one direction. Thus, by the suitable spatial arrangement of excitable fields in an asymmetric manner, the characteristics of a diode can be created between opposing excitable fields, even when the excitable fields exhibit the same excitability. This is in contrast to the current method used in electronics to produce a diode, i.e., different materials, such as *p*-type and *n*-type semiconductors, are connected to each other.

Using this unique character of a diode on an excitable field, logic gates with the operations AND, OR, and NOT have been shown to work [7]. Such logic gates naturally lead to ‘‘time-dependent’’ signals in the absence of any timing apparatus, i.e., without a ‘‘clock.’’ For example, the time-difference between input signals can be detected with a comblike arrangement of the excitable fields. To further extend the idea of field computation with an excitable system, the development of a memory device to store real-time input is indispensable.

It has been reported that rotating traveling waves can be generated in an annular excitable field in cellular systems and chemicals [5,8–10]. Unfortunately, there have been no successful reports on the spontaneous generation of a traveling wave in a desired direction.

In our previous paper, which used a numerical simulation with an excitable field, we suggested that a single input signal could be stored as a traveling wave in a circular excitable circuit by introducing the above-mentioned ‘‘diode’’ [7]. In the present paper, we report both a simulation and an actual experiment in which a memory device was created with a suitable spatial arrangement of an excitable field, and could be used to store a time series of input signals in a real-time sequence.

II. NUMERICAL RESULT

As an excitable field, we adopt the FitzHugh–Nagumo equation [11,12] without losing the generality

$$\tau\frac{\partial u}{\partial t}=-\gamma\{ku(u-\alpha)(u-1)+v\}+D\nabla^2u,$$

$$\frac{\partial v}{\partial t}=\gamma u, \tag{1}$$

where, for the case of a nerve cell, u represents the membrane potential in excitable nerve cells, and v is related to feedback ion-current along the membrane. Since the ion-current through the membrane in nerve cells is perpendicular to the direction of signal propagation, the diffusive term is present only in the time derivative of u and has no effect in that of v. The FitzHugh-Nagumo equation belongs to the so-called reaction-diffusion equation, where u and v represent the activator and inhibitor, respectively.

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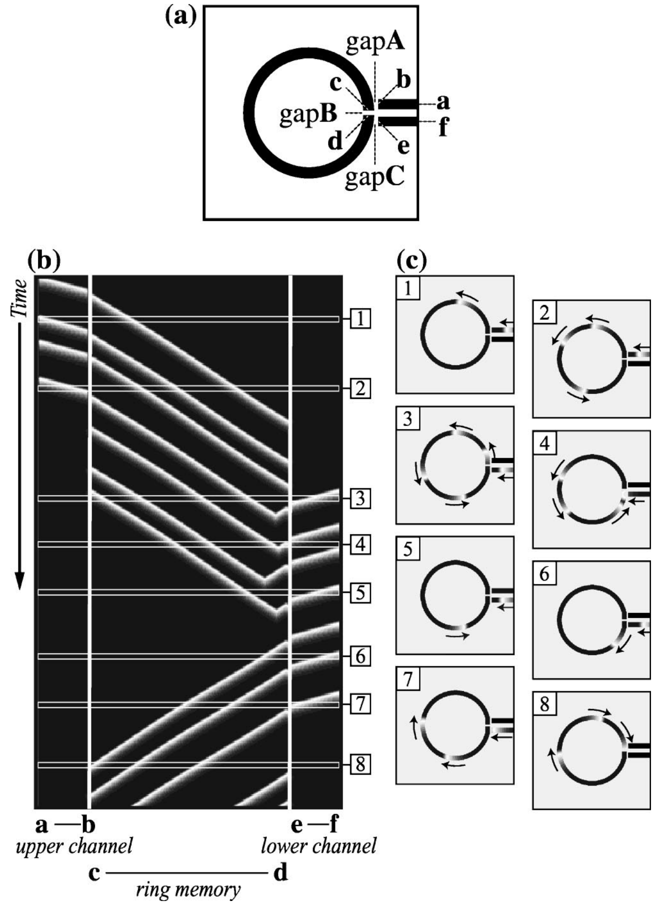

FIG. 1. (a) Geometry of the memory device. Black and white regions correspond to the excitable and diffusion fields, respectively. Input signals come from channel **a**–**b** or **f**–**e**, and propagate along the circular ring as real-time memory. (b) Space-time plot of traveling waves, where the space dimension is the projection of the circular ring together with the pair of input channels. The variable v in Eq. (1) is shown in quasi-color. Four successive input signals are introduced through channel **a**–**b**, and then seven pulses are introduced through the channel **f**–**e**. (c) Snapshot of the traveling waves in the actual geometry.

A. Real-time memory

Figure 1 shows the results of a simulation on the manner of traveling pulses propagation in the excitable circular track field. In the spatial arrangement in Fig. 1(a), the black and white regions correspond to the excitable field [$\gamma=1$ in Eq. (1)] and the diffusion field ($\gamma=0, v=0.0$). In Eq. (1), we set $D=0.000\,45$, $\tau=0.03$, $k=3.0$, and $\alpha=0.02$. The grid is a square lattice of 500×500 points, the time interval is $\triangle t=0.005$, and the space interval is $\triangle x=0.024$. The width of the gaps, **A**, **B**, and **C**, is 0.168. Figure 1(b) shows a spatio-temporal diagram while Fig. 1(c) shows snapshots of the actual manner of wave propagation. Four pulses are introduced from the input channel of **a**–**b** into the ring circuit through the gap **A**. The transmitted pulses then undergo counterclockwise rotation, indicating that clockwise propagation of the input signal is inhibited due to the presence of the gap **B**. The rotating counterclockwise waves can transmit through the gap **B**, since the direction of wave propagation is perpendicular to the channel of the intervening gap. Furthermore, the counterclockwise wave never transmits through the gap **A** or gap **C** (back-propagation), since the wave direction is parallel to the channels. These unique characteristics of wave propagation will be discussed later, in relation to the diode property in the excitable field.

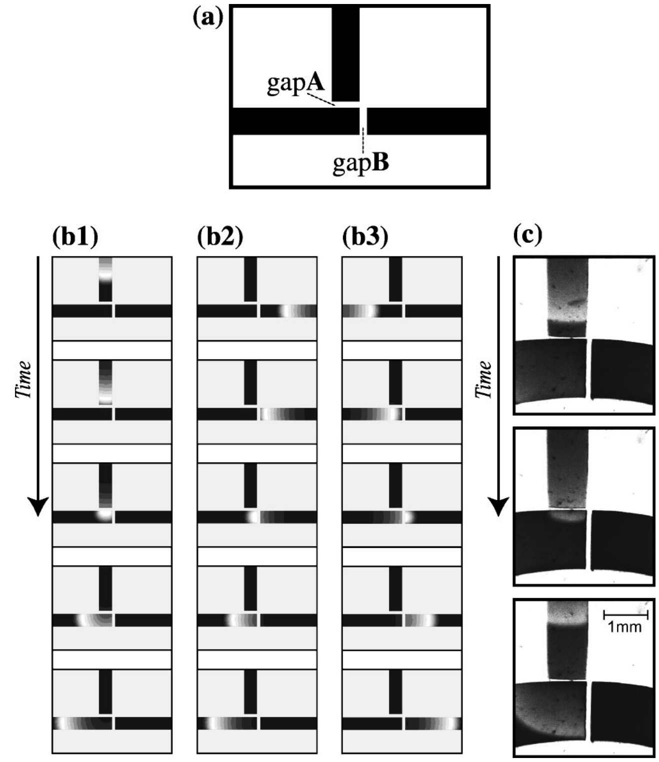

FIG. 2. (a) Functional unit for connecting the input channel and memory, where the black and white regions correspond to the excitable and diffusion fields, respectively. (b) Snapshot of the traveling waves. The variable v is shown in quasi-color. (b1) The wave from the upper channel can propagate to the left, but not to the right. (b2),(b3) The wave can propagate to the horizontal channel, but not to the upper channel. (c) An example of real experimental result, where the time intervals between frames are 34 s and 53 s.

Thus, it is clear that the counterclockwise pulses survive and retain the real-time sequence of the input signals. In Fig. 1, while the four waves maintain counterclockwise motion, seven pulses are introduced into the ring circuit from the input channel **f**–**e**, and the introduced pulses begin clockwise motion. The first four new waves collide with the counterclockwise pulses, and each pair of colliding pulses is annihilated. Finally, the three surviving pulses continue to rotate clockwise around the ring track. Thus, real-time memory can be erased and rewritten with new input information.

Let us briefly discuss the geometrical effect of wave propagation through a diffusion field. Figure 2(a) shows a device that has the characteristics of a diode, as in the corresponding region, between input channel and ring track in Fig. 1(a). The gaps, **A** and **B**, have the same width ($d=0.168$). With this geometry, as shown in Fig. 2(b1), the input signal transmits through the junction (gap **A**) to the horizontal track, and propagates only to the left. Such propagation can be described in terms of the diffusion length,

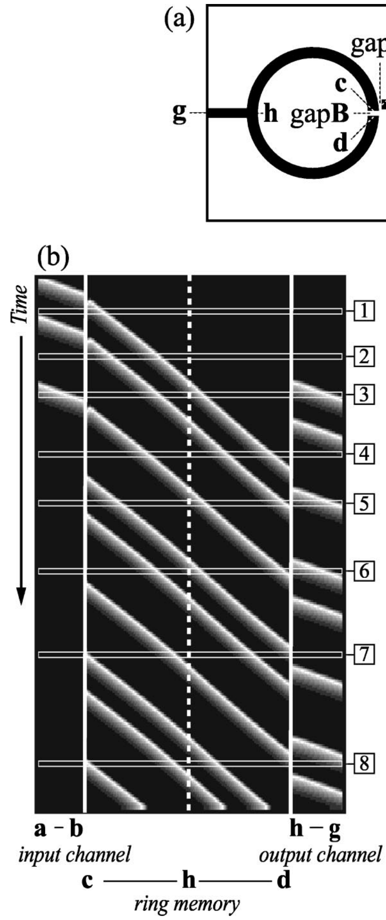

FIG. 3. (a) Geometry of the memory device equipped with an output channel **h**–**g**. (b) Space-time plot of traveling waves. Three successive input signals are introduced to the ring memory, and the three pulses are read out repeatedly through channel **h**–**g**. The broken line indicates the position of the output channel [**h** in (a)]. (c) Snapshot of the traveling waves.

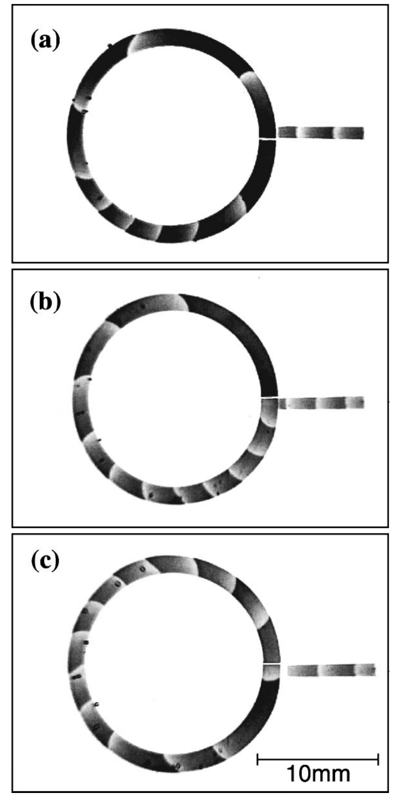

FIG. 4. Real-time memory in a real experiment (catalyst-doped BZ medium). (a) Successive input signals are introduced into the ring memory through the channel, and the pulses continue to rotate in the counterclockwise direction. (b) The input channel is shifted to a lower position, and input signals are then newly memorized as clockwise traveling waves. (c) Even after the input channel is disconnected, the memorized signals continue to rotate clockwise.

which depends on the direction of wave propagation [7]. Generally, the diffusion length of the propagating wave perpendicular to the boundary [e.g., in the gap **A** of (b1)] is greater than that parallel to the boundary [e.g., in the gap **A** of (b2) and (b3)]. Thus, even with the same gap width, an ''on/off'' property is generated. Figure 2(b2) and 2(b3), shows that the wave can propagate along the horizontal channel, but fails to propagate toward the upper vertical channel, which can be easily explained in terms of the unique diode characteristics. Figure 2(c) shows the same characteristics of Fig. 2(b1) in real experimental system, the BZ (Belousov-Zhabotinsky) reaction. We describe detail of this experimental system in the following experimental section, together with Fig. 4.

B. Readout of memory

Let us now discuss how to read the ''real-time'' information stored in the circular track. Figure 3 shows an example of reading the stored memory, where the time series of the three memorized pulses is repeatedly readout through the output channel **h**–**g**. The gaps, **A** and **B**, have the same width ($d=0.168$). In Fig. 3, three pulses are introduced from the input channel **a**–**b** into the ring circuit through the gap **A**. The transmitted pulses then undergo counterclockwise rotation. Each time the pulses approach the output gate at **h**, they propagate from the ring circuit toward channel **h**–**g**.

III. EXPERIMENTAL RESULT

We tried to examine the above idea in a real experiment. We used an oscillatory/excitable chemical reaction, the BZ reaction, on a reaction medium where the catalyst is fixed on an ion-exchange membrane. Such a reaction medium in the BZ reaction exhibits essentially the same characteristics as the excitable field described by the FitzHugh-Nagumo equation, Eq. (1); where the activator u and inhibitor v correspond to $HBrO_2$ and the metal catalyst fixed on the membrane, respectively [13]. It has been reported that a rotating traveling wave is generated on a circular track in a catalyst-doped BZ reaction, with a treatment by hands [8–10]. For example, a pair of traveling waves propagating in opposite directions was induced by local excitation, and wave was then annihilated by electrical stimulation. As the result, the other surviving wave continued to rotate on the ring track. In the present report, we tried to construct real-time memory in the BZ medium without any artificial treatment such as electrical stimulation.

Let us briefly describe the experimental procedure. A nafion cation-exchange membrane (Aldrich, Nafion 117, perfluorinated membrane, thickness: 0.18 mm) was used as the reaction medium in the BZ reaction [14,15]. Stock solutions of sodium bromate, sodium bromide, malonic acid (MA), and sulfuric acid were prepared with reagent-grade chemicals (Wako Pure Chemicals, Japan), where the final concentrations are 0.5, 0.02, 0.2, and 0.3 M, respectively. The water was purified with a Millipore Milli-Q filtering system, which was maintained at a resistivity of 18 MΩ. A catalyst [iron(II) tris-(1, 10-phenanthroline)(ferroin), Wako Pure Chemicals] loaded membrane was prepared by immersing the nafion membrane in 0.2 mM ferroin aqueous solution with stirring at room temperature [15]. The bathing solution became colorless within several hours after immersion, indicating that all of the catalyst was absorbed and immobilized on the nafion membrane. The membrane was then allowed to sit in place for one day. The catalyst-loaded membrane was then placed in the catalyst-free BZ solution at a depth of 3 mm to induce chemical waves on the membrane. The chemical waves were observed with a digital video camera (SONY, DCR-PC7). All measurements were performed at 300 ± 1 K.

Figure 4 shows the experimental results in the BZ reaction: (a) successive pulses are introduced into the ring track and sustained counterclockwise waves are observed. Here, such successive introduction has the effect of renewing the pulse train. Thus, the more recent time series of the input pulses is retained as ''dynamic memory;'' (b) When the input channels are shifted downward, the input pulses are memorized as clockwise pulses by erasing the counterclockwise pulses; (c) Even after the input channel is moved away from the ring circuit, the clockwise pulses continue to rotate, retaining the information of the pulse train.

IV. DISCUSSION AND CONCLUSION

Past studies on memory in the brain have suggested that there are at least two types of memory, short-term and long-term [16]. Short-term memory lasts from a fraction of a second to several seconds, and is expected to correspond to a specific dynamic firing pattern. Although such a hypothesis regarding short-term memory is tempting, to the best of knowledge there is still no definite experimental evidence from actual neural systems to support it. In the present study, we have shown that such short-term memory can actually exist on an excitable field with suitable geometry.

In current studies on artificial neural networks, usually a ''synapse junction'' is given *a priori*, i.e., diode character is not attributed to the spatial geometrical effect on an excitable field, but rather to the difference in the chemical network of the opposing parts in the excitable field. In our present and previous studies [7], we have shown that a spatially arranged geometrical field can reflect a time-operation and exhibit real-time memory. Since the strategy of field operation is simple and the diode can be produced with a homogeneous material, efforts to construct a ''field computer'' may be promising for future massive computation. A remaining problem is how to obtain a conventional excitable field on a reliable solid circuit to construct a field computer.

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