A memristor-based associative memory circuit considering synaptic crosstalk

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April 12, 2022

Abstract

Synaptic crosstalk, which characterizes the interaction between synapses when the neighboring neurons are activated at the same time, plays an important role in the transmission of neural signals. To discover the effect of synaptic crosstalk on associative memory, a memristor-based associative memory circuit considering synaptic crosstalk is proposed in this letter. The inhibitory effect of negative crosstalk on associate memory in the initial learning stage and the consolidation influence of positive crosstalk on associate memory when the synaptic weight exceeds the critical value are revealed. Pspice simulations are conducted on the resultant circuit to verify its correctness.

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Synaptic crosstalk, which characterizes the interaction between synapses when the neighboring neurons are activated at the same time, plays an important role in the transmission of neural signals. To discover the effect of synaptic crosstalk on associative memory, a memristor-based associative memory circuit considering synaptic crosstalk is proposed in this letter. The inhibitory effect of negative crosstalk on associate memory in the initial learning stage and the consolidation influence of positive crosstalk on associate memory when the synaptic weight exceeds the critical value are revealed. Pspice simulations are conducted on the resultant circuit to verify its correctness.

Introduction: Pavlov's dog is a representative experiment to verify associative memory, which is a memory method that connects memories with things one has experienced. Taking advantage of the excellent performances of memristor, such as low power consumption, non-volatile, plasticity and nano scale, numerous memristor-based associative memory circuits have been proposed. For example, a memristance changing circuit is designed to achieve the formation of associative memory in [1]. Time-delay effects on associative memory circuit were explored in [2]. Secondary conditional reflex in associative memory circuit was also reported in [3]. Synaptic crosstalk, induced by transmitter spillover from the synaptic cleft and its diffusion over a distance to neighboring synapses, is a ubiquitous phenomenon in several brain regions [4]. Due to the interaction between synapses, synaptic crosstalk plays a very important role in the transmission of neural signals. Leng *et al* . revealed the dynamic behaviors of a Hopfield neural network infected by synaptic crosstalk [5]. However, the effects of synaptic crosstalk on associative memory are rarely reported in the previous literature. Motivated by this consideration, we propose a circuit to explore the effects of negative and positive synaptic crosstalk on associative memory circuit.

Memristor model: In this letter, a threshold memristor model is used to mimic the function of biological synapses, which is described as [3]

where $M\ (t\ )$ is the memristance, $\omega\ (t\ )$ is the width of the high doped region, and D is the full thickness of memristive material. R_{ON} andR_{OFF} denote the maximum and minimum value of memristance, respectively. The derivative of the state variable in the threshold memristive model is

where $i_{\ 0}$, i_{off} , and$i_{\text{ on}}$ are constants, $v\ (t\ )$ is the applied voltage of the memristor, μ is the average the mobility of i_{on} ,V_{TH+} and $V_{TH\text{-}}$ are the positive and negative threshold voltages, respectively,$f\ (\omega\ (t\ ))$ is a window function and p is a positive integer. The memristor parameters used in this letter are listed in Table 1.

Table 1: Parameters setting of memristors

Paramerters	M_1	M_2	M_3, M_4	
R_{INT}(kΩ)	0.2	0.7	0.5	0.5
R_{ON}(kΩ)	0.01	0.1	0.1	0.1
R_{OFF}(kΩ)	1	1	1	1
V_{TH+}(V)	+ 3.5	+ 0.1	+ 0.1	+ 0.1
$V_{TH\text{-}}$(V)	- 0.1	- 0.1	- 0.1	- 0.1

Neural network model: As shown in Fig.1, two input neurons “ring” and “food”, which can be activated by corresponding stimuli are connected to a output neuron “saliva” by two memristive synapses. According to pavlov’s experiment, the stimulus of food can lead to the response of salivation without any training or experience, this inherent stimuli-response is called unconditional reflex. Therefore, the synaptic weight of W_1 is set to high weight. When the stimuli of ring appears alone, the dog does not salivate in the initial stage. This is because unlearned conditioned reflex does not induce the dog’s saliva response, so that the synaptic weight of W_2 is initially set to low weight. When both of “ring” and “food” neurons are activated at the same time, the weight of W_2 will increase. Synaptic crosstalk only occurs when both neurons are activated at the same time [6], this is because the neurotransmitter pathways between synapses are opened only when neighboring synapses are activated at the same time. At the initial learning stage, the connection between “ring” and “saliva” is weak. The negative crosstalk between synapses of “ring” and “food” emerges to inhibit the increase of learn-induced synaptic weight W_2. Once the weight of W_2 exceeds its critical value, the crosstalk will be transformed into the positive crosstalk to consolidate the effect of associative memory.

Fig. 1 *The associative memory network with synaptic crosstalk.*

Synaptic weights considering crosstalk can be written as

where $K_{\ 1}$ and $K_{\ 2}$ are the crosstalk strengths, $g\ (\cdot\ )$ represents the crosstalk function between the two neighboring synapses. In this letter, we use the conductance of memristor to represent the synaptic weight.

Fig. 2 *The circuit implementation of Pavlov associative memory considering synaptic crosstalk.*

Circuit structure: Based on the proposed neural network model, an associate memory circuit is proposed. As illustrated in Fig.2, the circuit is composed of two parts: one is the basic associative memory circuit labeled with black line, which can realize the functions of associative learning and forgetting. The other is the channels of synaptic crosswalk, which is labeled with red lines. The circuit parameters are chosen as $R_1 = R_2 = 100\ \Omega$, R_2 ˜ $R_{13} = 1k\ \Omega$. P_1 ˜ P_4 are P-MOSFETs with the threshold voltage of -2 V, P_3 is the P-MOSFET with the threshold voltage of -3.8 V, P_5 is the P-MOSFET with the threshold voltage of -2.4 V, T_1˜ T_4 are N-MOSFETs with the threshold voltage of 2 V. The input voltage amplitude of “ring” and “food” are 3 V. SUM is the mathematical component for voltage summation. The parameters of the used memristors are shown in Table 1.

The associative learning occurs only when “ring” and “food” appear at the same time, and the weight of W_2 increases following the direction of the blue arrow. During the process of forgetting, the dog receives “ring” or “food” separately. In this stage, the adjustment path for the weight of W_2 follows the direction of the black arrow, and the weight of W_2decreases. It is worth noting that there exists a critical value W_2

= 4.1mS, which is obtained by numerous simulation analyses. When $W_2 > 4.1$ mS, the associative memory between "ring" and "saliva" is formed. When $W_2 < 4.1$ mS, on the contrary, there is a weak correlation between "ring" and "saliva".

The red-line labeled circuit in Fig. 2 is the channels through which crosstalk signals are generated and transmitted. The voltage divider consisting of a memristor and a resistor is utilized to simulate the variation of crosstalk intensity $K_{1,2}$with time. Two types of crosstalk are considered in Fig. 2: 1) Negative crosstalk: During the initial stage of learning, crosstalk between synapses of "ring" and "food" prevents the increase of W_2. Only when $V_{A1} > -1.2$ V, P_5 is turned off, so that U_{10} has no output. While U_8 outputs a high-level voltage that causes U_9 to output a high voltage, and T_3 is turned on. Then the negative voltage of -1.2 V is applied to M_2 through a voltage divider composed of M_3 and R_{12}, which represents the negative crosstalk from M_1 to M_2. Similarly, for the synapse M_2, P_4 is turned off when $V_{A2} > -0.8$ V, then U_5 outputs a high voltage, which causes U_7 to output a high-level voltage. Thus, T_4 is on and the voltage of -1.2 V is delivered to M_1 as negative crosstalk through a voltage divider composed by M_4 and R_{13}. 2) Positive crosstalk: When $W_2 > 4.1$ mS, there is positive crosstalk between synapses of M_1 and M_2 to enhance the associative memory. $P_5$is on and T_3 is off as long as $V_{A1} < -1.2$ V. Thus, 1.2 V is applied to U_{10}, which causes U_{10} to output a high voltage 1.5 V. Then 1.5 V considered as positive crosstalk signal is transferred to M_2 through the voltage divider composed by M_3 and R_{12}. In the similar way, P_4 is turned on only when $V_{A2} < -0.8$ V, then U_6 outputs a voltage of 1.5 V. Then, the 1.5V voltage, regarded as positive crosstalk signal, is transferred to M_1 through the voltage divider composed by M_4 and R_{13}.

Fig. 3 *Pspice simulation of the processes of associative memory.*

Pspice simulation: In order to verify the correctness of the proposed circuit, Pspice simulations are conducted on the resultant circuit and the corresponding simulation results are illustrated in Fig. 3.

During the first test stage (0 ~ 3 s), it is to verify whether the initial relationships between the input neurons and the output neuron are correct. The output neuron "saliva" is active when the food stimulus is applied. In biology, there is an inherent relationship between food stimulus and salivation response, called an unconditional reflex. When the ring stimulus is provided alone, "saliva" has no output, meaning that the ring is a neutral stimulus.

Then, in the initial learning stage (3 ~ 6 s), both of the food and ring stimuli are applied to the dog, saliva neuron is activated and outputs a high voltage. In this stage, the weight of W_2 between "ring" and "saliva" increases and the synaptic crosstalk emerges. As illustrated in Fig.3, the weight of W_2 without crosstalk increases more quickly than the one with crosstalk, and firstly reaches the critical value 4.1 mS. It is obvious that the crosstalk, in the initial learning stage, is negative crosstalk with $K_{1,2} < 0$, which inhibits the increasing rate of the weight of W_2.

In test$_2$ (6 ~ 7 s), for the case without crosstalk, the saliva neuron is activated when the ring stimulus is provided alone. This means that the associative memory between ring and salivation has been formed after the initial learning. However, for the case with crosstalk, the synaptic weight of W_2 does not reach its critical value 4.1 mS during the initial learning stage. So, the mechanism of associative memory has not been formed, resulting in that the dog does not salivate under the stimulus of the ring during the second test stage (6 ~ 7 s). The above comparison shows that negative crosstalk has an inhibition effect on the formation of associative memory.

In the second learning stage (7 ~ 15 s), both of the food and ring stimuli are applied to the dog once again. For the case with crosstalk, the weight of W_2 reaches the critical value 4.1 mS at 7.3 s and then the positive crosstalk occurs with $K_{1,2} > 0$. In this case, the weight of W_2 with crosstalk begins to increase rapidly. After a period of studying, it surpasses the weight of W_2 without crosstalk. So, at the end of the second learning stage, the weight of W_2 with crosstalk reaches a higher value than the one without crosstalk.

In the following forgetting stage (15 ~ 20 s), the ring stimulus is applied separately. Due to the presence of only ring stimulus, there is no synaptic crosstalk. One can find that the duration of memory with crosstalk is 15 ~ 19 s, and it is longer than the one without crosstalk (15 ~ 18.5 s). Thus, it is confirmed that positive crosstalk can consolidate associate memory and prolong the duration of memory. Furthermore, it can be clearly seen that the crosstalk strengths K_1 and K_2 change with time evolution. When $K_1$and K_2 are negative, they represent as a negative crosstalk strength, which will be weakened with the increase of learning time. On the contrary, they stand for a positive crosstalk strength, which will be strengthened with the increase of learning time.

Conclusion: Although a lot of research has been done on associative memory circuits, the effects of synaptic crosstalk on associative memory are rarely reported. In this letter, a novel memristor-based associative memory circuit is developed, in which the effects of the synaptic crosstalk on associative memory are focused on. We find that the negative synaptic crosstalk emerges before the generation of associative memory mechanism, which inhibits associative memory; once the associative memory mechanism is established, the crosstalk manifests itself as positive crosstalk, which can prolong the duration of memory. Pspice simulations are performed to verify the correctness of the proposed circuit.

Acknowledgements: This work was supported by the National Natural Science Foundations of China under Grant No. 62071411.

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