A memristor-based associative memory circuit considering synaptic crosstalk

Zhijun Li¹ and zhaowei yi¹

¹Xiangtan University

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.

A memristor-based associative memory circuit considering synaptic crosstalk

Zhijun Li, and Zhaowei Yi

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 was 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. $R_{ON}$ and $R_{OFF}$ denote the maximum and minimum value of memristance, respectively. The derivative of the state variable in the threshold memristive model is

$$i(t) = i_0 \cdot \mu \cdot \left( |v(t)| - V_{TH} \right) \cdot f(\omega(t))$$

where $i_0$, $i_{off}$, and $i_{on}$ are constants, $v(t)$ is the applied voltage of the memristor, $\mu$ is the average the mobility of $i_{on}$, $V_{TH+}$ and $V_{TH-}$ 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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$M_3$, $M_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{INT}(k\Omega)$</td>
<td>0.2</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>$R_{ON}(k\Omega)$</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$R_{OFF}(k\Omega)$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$V_{TH+}(V)$</td>
<td>+ 3.5</td>
<td>+ 0.1</td>
<td>+ 0.1</td>
</tr>
<tr>
<td>$V_{TH-}(V)$</td>
<td>- 0.1</td>
<td>- 0.1</td>
<td>- 0.1</td>
</tr>
</tbody>
</table>

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.](image)

Synaptic weights considering crosstalk can be written as

$$W_{2} = K_1 \cdot g(\cdot) + K_2 \cdot g(\cdot)$$

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 crosstalk, which is labeled with red lines. The circuit parameters are chosen as $R_1 = R_2 = 100 \Omega$, $R_3 \sim R_{13} = 1k \Omega$. $P_1 \sim P_4$ are P-MOSFETs with the threshold voltage of -2 V, $P_5$ 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, $T_1 \sim T_4$ are N-MOSFETs with the threshold voltage of 2 V. The input voltage amplitudes 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 $W_2$ decreases. It is worth noting that there exists a critical value $W_2$.
For the case with crosstalk, the weight of $W_{2}$ in the second learning stage (7 ˜ 15 s) is applied to the dog once again. Both of the food and ring stimuli are applied to the dog, resulting in the formation of associative memory. 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 $U_{6}$ 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 $R_{13}$. 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. $P_{4}$ 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.](image)

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

$=$ 4.1 mS, 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”.
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.

**References**


Hosted file

Hosted file
Fig. 2.docx available at [https://authorea.com/users/475797/articles/564981-a-memristor-based-associative-memory-circuit-considering-synaptic-crosstalk](https://authorea.com/users/475797/articles/564981-a-memristor-based-associative-memory-circuit-considering-synaptic-crosstalk)

Hosted file
Fig. 3.docx available at [https://authorea.com/users/475797/articles/564981-a-memristor-based-associative-memory-circuit-considering-synaptic-crosstalk](https://authorea.com/users/475797/articles/564981-a-memristor-based-associative-memory-circuit-considering-synaptic-crosstalk)

Hosted file