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A new neuron model under electromagnetic field ☆

Fuqiang Wu [a,b,*], Jun Ma [b], Ge Zhang [b]

[a] School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China
[b] Department of Physics, Lanzhou University of Technology, Lanzhou 730050, China

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ABSTRACT

Fluctuation of membrane potential occurs when the concentration of ions, e.g., Calcium, Potassium, Sodium, in the cell is changed. When external electric stimulus beyond threshold is applied, action potential can be induced to predict the changes in distribution density of ions, which can also trigger time-varying electric field and magnetic field. For example, each static charge can induce spatial distribution of electric field while any moving charge can generate distribution of magnetic field. In this paper, a neuron is considered as a complex charged body and the effect of electromagnetic field is considered to build a new neuron model, which magnetic flux and charges is used to describe the variation of magnetic field and electromagnetic induction, electric field, respectively. The physical neuron model is then described by dimensionless dynamical system after scale transformation and then is verified on analog circuit platform. Nonlinear analysis is practiced on this new neuron model and external electromagnetic radiation is applied to detect the mode transition and response in neuronal activities. The electrical activities can be modulated when the band of electromagnetic radiations is adjusted. It can throw light on investigation of neurodynamics and experimental practice in neural circuits.

1. Introduction

The biological nervous system is made of a large number neurons with complex connection type, and the signal encoding and propagation [1–5] between neurons and astrocytes can regulate the muscle to behave normal gait and movement. For example, the release and change of Calcium concentration can adjust contraction and relaxation of muscle. Many neuron models [6–9] have been proposed to reproduce the electrical activities of neurons and the outputs are triggered to generate the similar phase and modes such as quiescent, spiking, bursting and even chaotic states. Based on these theoretical neuron models, bifurcation analysis, synchronization transition and pattern selection on the neural network have been investigated extensively. On the other hand, experts in engineering and physics have tried to build a variety of neural circuits [10–14] thus the processing of electric signals from biological cells can be reproduced in nonlinear circuits. Furthermore, more evidences have confirmed that astrocyte [15] also contributed much to regulate the electrical activities in nervous system. As a result, some neuron-coupled astrocyte network [16–19] models were proposed to detect the signal processing and propagation between neurons.

The electrical activities in neuron models and biological experiments have been extensively investigated to discover potential mechanism of information encoding and signal processing in the nervous system [20–23]. The biological neu-

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* Corresponding author at: School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China.
E-mail address: alextianming@126.com (F. Wu).

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ron models often consider the effect of ion channel and diffusion along the axon, while some simplified neuron models just emphasize the transition and selection in modes of electrical activities [24–26]. Electrical activities in the biological Hodgkin-Huxley model can be reproduced from the synergistic action between sodium and potassium ion channels which are dependent on voltage threshold [27]. As a result, modulation of channel conductance [28–31] such as blocking in ion channels can regulate the electrical activities effectively. That is, reliable neuron models are very important to reproduce and analyze the electrical activities in biological neurons. For example, Gu et al. [32] confirmed that bifurcations from bursting to spiking in the biological experiments can be presented by the theoretical model. Furthermore, neural networks are built to detect the synchronization transition [33–37] and pattern selection [38–41] when chemical and electric synapse connections are activated. Indeed, collective behaviors are much dependent on the local kinetics when the topology connection is fixed. Therefore, reliable neural circuits [42–44] are important to investigate the nonlinear response of network composed of circuits.

Polarization and magnetization occur when the media is exposed to electromagnetic field, as a result, the distribution of charges and electric field in the cells are rearranged and regulated to change the response in membrane potential. On the other hand, the movement and transports of ions can change the field distribution, thus the membrane potential can also be modulated. On the other hand, it gives clues that external electromagnetic field can be applied to affect the electrical activities in brain and nervous system. The brain is thought as the most intelligent nervous system, the principle of electromagnetic induction has been mentioned in the early years, and its utility and potential capabilities have been also demonstrated [44–47]. The amplification of information in excitable systems was investigated by bifurcation [48]. Like the nuclear magnetic resonance, this technique has been used to stimulate both the central and peripheral nervous system. It has been confirmed to have potential application as a diagnostic and therapeutic tool. For example, appropriate models have been presented under magnetic stimulation [49,50]. With the development of quantum detects in the diamond chip, time-varying magnetic fields generated by action potential can be demonstrated in a single neuron under a noninvasive condition [51], and then this mechanism is explained according to reasonable neuron model by using the mathematical-physical approaches. For example, electrical activity is simulated in neuron and cardiac tissue when magnetic flux and induction current are used to describe the effect of electromagnetic induction while memristor is used to bridge connection between magnetic flux and membrane potential [52–55]. In fact, it is important to develop a more reliable neuron model so that both the effect of electric field and magnetic field can be considered together. In this paper, a physical neuron model is built to consider the electrical activities of neuron by introducing the charge flux and magnetic flux, then time-varying electromagnetic field is applied to discuss the radiation effect. The equivalent analog circuit is also designed and external magnetic stimulus coil is activated to produce external electromagnetic radiation.

2. Model descriptions

As is well known, a capacitor can induce time-varying electric field when the plates are charged or discharged continuously. While an inductor can generate time-varying magnetic field in the induction coil when charge flow are transmitted with time. From physical view, the neuron can be thought as neural circuit which can be built by using capacitor, inductor and necessary other electric devices. The exchange of field energy can modulate the outputs in the circuit and external electromagnetic energy can also be absorbed by the capacitor and inductor. Therefore, the generic circuit equation can be described by

$$\begin{cases} C_m \frac{dV}{d\tau} = F(V,i) + I_{ext}; \\ L_m \frac{di}{d\tau} = G(V); \end{cases} \tag{1}$$

where V is the membrane voltage, and i denotes the recovery variable relevant to transmembrane current. I_{ext} is the external forcing and synapse current. The term $F(V, i)$ describes the current function which is dependent on the membrane voltage and recovery current. $G(V)$ represents the voltage function associated with magnetic field. C_{m} is membrane capacitance which is dependent on the property of the media, L_{m} is the equivalent inductance of the neuron. In fact, continuous transmission of ion flow from dendrite to soma or any movement in the cell can generate magnetic field. For example, a spherical shell with charge has the electric field around itself from the point of view of physics. As a result, the time-varying distribution of charges or ions can induce complex electromagnetic induction, which can be described by induction field. For simplicity, a schematic representation of the soma and dendrite with the time-varying electromagnetic field is plotted in Fig. 1.

According to the mentioned physical assumption, the flux of electric field Φ_E across soma surface (S) and current can be estimated as follows

$$\begin{cases} \Phi_E = \int_S \vec{E} \bullet d\vec{S} = \frac{q}{\varepsilon_E}; \\ \frac{dq}{dt} = i; \end{cases} \tag{2}$$

where E denote the intensity of electric field and q represents the charge. The dielectric constant ε_E is dependent on the intrinsic property of the media. Then a magnetic flux is introduced to describe the effect of magnetic field because continuous ion flux can trigger time-varying magnetic field. Inspired by the effect of electromagnetic induction [52], the magnetic

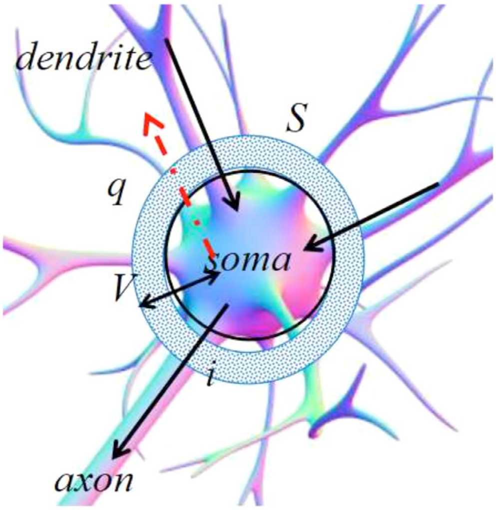

Fig. 1. Schematic diagram of a single neuron with dendrite, soma and axon, V, i are the membrane potential and ion current, respectively.

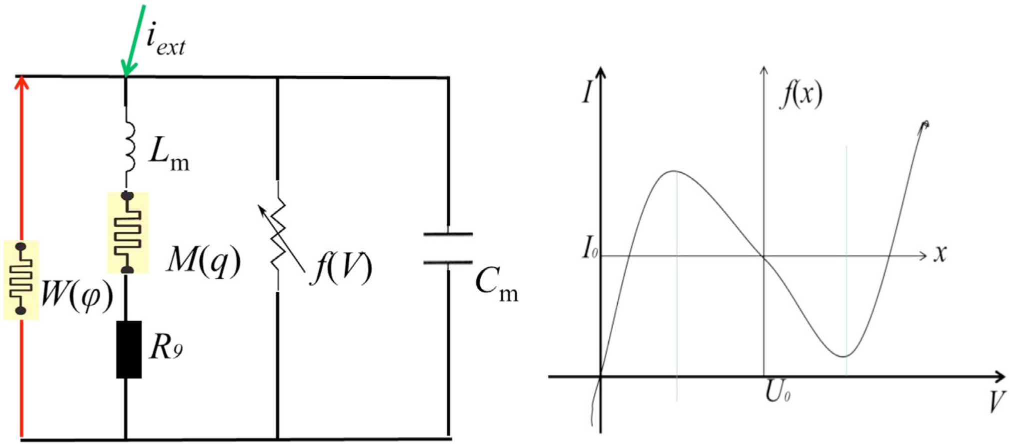

Fig. 2. Schematic diagram of neural circuit and I-U(current vs. voltage) relation for tunnel diode. R_9, C_m, L_m are the resistance, capacitor, and inductor, respectively. $f(V) = V^3/3 - V$ denotes the relation between voltage and current on the tunnel diode and the current across the diode is approached by $I_1 = I_0 f(V)$, $W(\varphi)$ is associated with magnetic flux-controlled memristor and the induction current is approached by $W(\varphi)V$, $M(q)$ is relative to charge-controlled memristor and the induction potential on the cell is calculated by $iM(q)$.

flux (φ) of a cross-section (S) and induced electromotive force (V) can be calculated as follows

$$\begin{cases} \iint_s \vec{B} \bullet d\vec{S} = \varphi; \\ \frac{d\varphi}{dt} = -V; \end{cases} \tag{3}$$

Furthermore, a generic neuron model and circuit can be built when the effect of electric field and magnetic field are considered simultaneously. These physical variables are approached by

$$\begin{cases} C_m \frac{dV}{d\tau} = F(V,\ i) + I_{ext} + I_{induction}; \\ L_m \frac{di}{d\tau} = G(V) - V_{induction}; \\ \frac{dq}{d\tau} = i; \\ \frac{d\varphi}{d\tau} = -V; \end{cases} \tag{4}$$

where $I_{induction}$ denotes the induction current induced by time-varying magnetic field, and its relationship is given as $I_{induction} = W(\varphi)V$. $V_{induction}$ represents the induction potential resulting from the time-varying electric field, and its relationship is defined as $V_{induction} = M(q)i$. For simplicity, the nonlinear relation between membrane potential and current is described by the classical FitzHugh-Nagumo model [56], the circuit diagram of the neuron with charge and magnetic flux is plotted in Fig. 2.

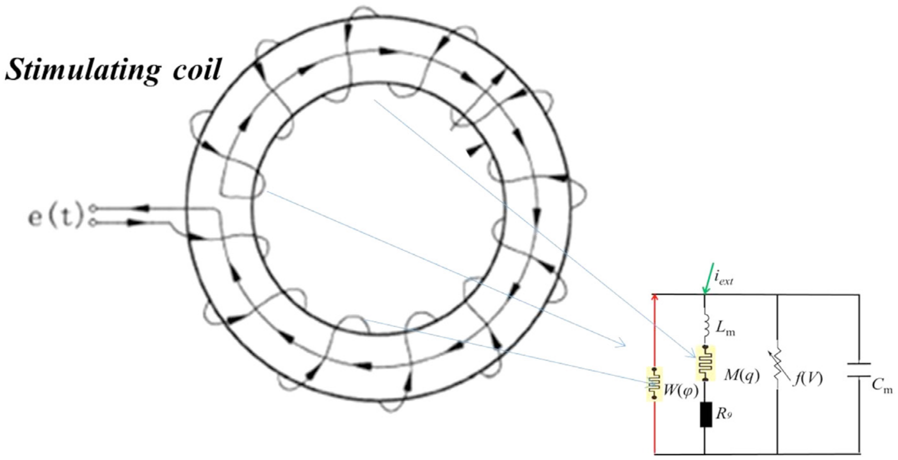

Fig. 3. A simple configuration of magnetic stimulation on the neural circuit.

Some evidences have confirmed the emergence and occurrence of extracellular electric field in neuron [49]. A magnetic flux-controlled memristor is used to detect the induction current while another charge flux-controlled memristor is used to calculate the induction potential associated with induction field. The generic mathematical formats for charge-controlled memristor [57] and magnetic flux-controlled memristor [58] are respectively defined by

$$\begin{cases} M(q) = \frac{d\varphi(q)}{dq} = R(a) + \eta(b)q^2 = \frac{R'R_0}{R_a} + \frac{R'R_0}{R_b C_m^2 U_0^2} q^2; \\ W(\varphi) = \frac{dq(\varphi)}{d\varphi} = G(\alpha) + \eta(\beta)\varphi^2 = \frac{R'}{R_0 R_\alpha} + \frac{3R'}{R_0 R_\beta L_m^2 I_0^2}\varphi^2; \end{cases} \tag{5}$$

where $R(a)$ and $G(\alpha)$ are the constant resistance and conductance under equilibrium state, respectively. $\eta(b)$ and $\eta(\beta)$ are the rate of change for charge and magnetic flux, respectively. These parameters are dependent on the properties of neuron, while R_a, R_α, R_b, R_β, R', are parameters prepared for the following scale transformation and circuit application. According to the Kirchhoff's voltage and current laws, the circuit as depicted Fig. 2 is calculated by

$$\begin{cases} C_m \frac{dV}{d\tau} = V - \frac{V^3}{3} - i + i_{ext} + W(\varphi)V; \\ L_m \frac{di}{d\tau} = V - iR_9 - M(q)i; \\ \frac{dq}{d\tau} = i; \\ \frac{d\varphi}{d\tau} = -V; \end{cases} \tag{6}$$

The potential scale transformation is applied to get dimensionless dynamical system as follows:

$$\begin{cases} x = \frac{V}{U_0}, y = \frac{i}{I_0}, z = \frac{q}{C_m U_0}, w = \frac{\varphi}{L_m I_0}, t = \frac{\tau}{\sqrt{C_m L_m}}; \\ I_{ext} = \frac{i_{ext}}{I_0}, R_0 = \frac{U_0}{I_0} = \sqrt{\frac{L_m}{C_m}}; \\ \alpha = \frac{R'}{R_\alpha}, \beta = \frac{R'}{R_\beta}, a = \frac{R'}{R_a}, b = \frac{R'}{R_b}; \\ k_1 = \frac{R_3}{R_1}, k_2 = \frac{R_9}{R_{10}}, k_3 = \frac{R_{17}}{R_{11}}, k_4 = \frac{R_{20}}{R_{18}}, \end{cases} \tag{7}$$

where the dimensionless parameters are introduced as k_1, k_2, k_3, k_4, $R_{10} = R_0$, and R_1, R_3, R_9, R_{10}, R_{11}, R_{17}, R_{18}, R_{20} are resistors used in building the neural circuits. Then the dimensionless neuron model is described by

$$\begin{cases} \frac{dx}{dt} = -\left(\frac{x^3}{3} - k_1 x\right) - y + I_{ext} + \lambda_H(\alpha + 3\beta w^2)x; \\ \frac{dy}{dt} = x - k_2 y - \lambda_E(a + bz^2)y; \\ \frac{dz}{dt} = k_3 y; \\ \frac{dw}{dt} = -k_4 x; \end{cases} \tag{8}$$

where x, y, z, and w represent the voltage, current, charge, and magnetic flux without dimension, respectively. λ_H and λ_E represents the switching factor of the magnetic and electric field, $\lambda_H = \lambda_E = 1$ means that both magnetic field and electric field are considered, $\lambda_H = \lambda_E = 0$ means that the effect of magnetic and electric field is not considered. Furthermore, when external electromagnetic radiation is imposed, an inductor coil is used to generate electromagnetic radiation on the neural circuit, this process can be illustrated in Fig. 3.

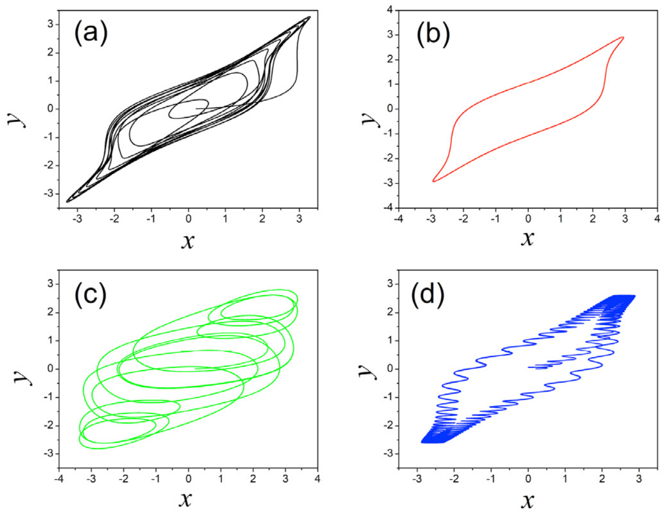

Fig. 4. Phase portraits between membrane potential and current in an isolate neuron by applying different external stimuli. $I_1 = I_2 = 6.0$, $f_1 = 0.06$, for (a) $f_2 = 0.006$; (b) $f_2 = 0.06$; (c) $f_2 = 0.66$; (d) $f_2 = 6.66$, no electromagnetic field effect considered as $\lambda_E = 0.0$, $\lambda_H = 0.0$.

That is, the magnetic stimulation is induced by a circular induction coil. Then its equation for the single neuron exposed to electromagnetic radiation is given by

$$\begin{cases} \frac{dw}{dt} = -k_4 x + H_{ext}; \\ H_{ext} = V_{th} e^{(-A_0 t)} [A_1 \cos(B_1 t) + A_2 \sin(B_2 t)]; \end{cases} \tag{9}$$

where H_{ext} denotes the external electromagnetic radiation induced by a stimulator coil, V_{th} is the induction potential threshold. A_0, $A_{1,}$ A_2, $B_{1,}$ B_2 are the damping ratio, amplitude, angular frequency of radiation source, respectively. When large diversity in $B_{1,}$ B_2 occurs, it means that both of low frequency and high frequency signals [59] are imposed on the neuron simultaneously.

3. Numerical results and discussions

In the numerical studies, the fourth Runge-Kutta algorithm is used to find solutions for dynamical equations with time step $h = 0.01$ by using the ODE45 function in Matlab 2014. The initial values for an isolate neuron model are set as (x_0, y_0, z_0, w_0) = (0.2, 0.01, 0.2, 0.01). Charge-controlled memristor and magnetic flux-controlled memristor can describe nonlinear electrical activities by selecting parameters as, $a = 0.2$, $b = 0.1$, $\alpha = 1.0$, $\beta = 0.02$. Other parameters are fixed at $k_1 = 1.0$, $k_2 = 1.0$, $k_3 = 1.0$, $k_4 = 0.01$. As is well known, the excitability of neuron can be changed by external forcing current, as mentioned in Ref. [59], multi-channel signal is imposed on the neuron to detect the electrical response by imposing additive periodic signals as $I_{ext} = I_1 \sin(\pi f_1 t) + I_2 \cos(\pi f_2 t)$ synchronously. Here, the same signal composed of two different frequencies is applied on the neural circuit, the results are shown in Fig. 4.

The profile of attractors and phase portraits are dependent on the frequency of external stimulus because the excitability can be modulated by the external forcing. To further investigate the mode dependence of electrical activities on external stimulus, the frequency band $\Delta f = f_2 - f_1$ and amplitude gradient $\Delta I = I_2 - I_1$ in external stimulus are selected with different values at $f_1 = 0.06$, and the interspike intervals(*ISIs*) from membrane potential series are calculated for bifurcation analysis, and the results are shown in Fig. 5.

The bifurcation diagram in Fig. 5 confirmed that multiple peaks can be found in the sampled time series for membrane potentials and thus multiple modes can be induced in the electrical activities. Furthermore, the time-varying electromagnetic field is considered and the electrical activities of an isolate neuron are calculated in Fig. 6.

The results in Fig. 6 confirmed that phase orbits become dense and periodic attractor is converted into chaotic attractor and even multi-scroll attractors can be formed. Furthermore, the bifurcation analysis is carried out by setting different frequency bands when the amplitude of external forcing is fixed, and the results are shown in Fig. 7.

The bifurcation diagram in Fig. 7 confirmed the emergence of multiple modes in the electrical activities and even chaos can be induced when electromagnetic field is activated. And firing patterns become more complex at the low frequency. Thus the outputs are calculated to observe the profile of firing pattern at fixed the external forcing current as $I_1 = I_2 = 6.0$, $f_1 = 0.06$, $f_1 = 0.006$, and the results are plotted in Fig. 8.

In Fig. 8, the pattern of transitions from periodic oscillator to multi-periodic bursting can be regulated by system parameters (α), which plays an important role in understanding the electrical activity such as propagation, generation, and encoding. Extensive numerical results also confirmed that the parameter β can cause more distinct modulation on

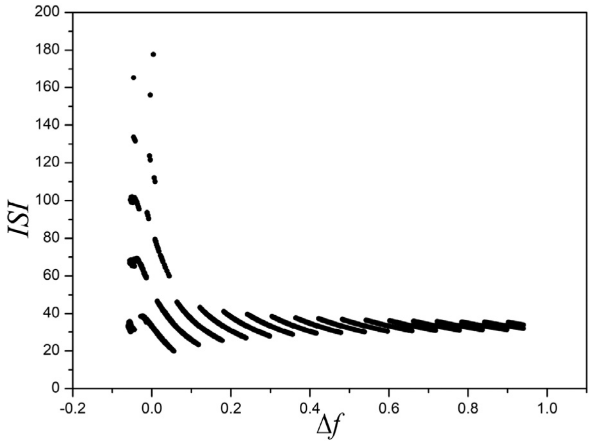

Fig. 5. Bifurcation diagram *ISI* (calculated from the time series for membrane potential of neuron) vs. frequency band Δf. The parameters are set as $I_1 = I_2 = 6.0$, $f_1 = 0.06$ and the electromagnetic field is not considered as $\lambda_E = 0.0$, $\lambda_H = 0.0$.

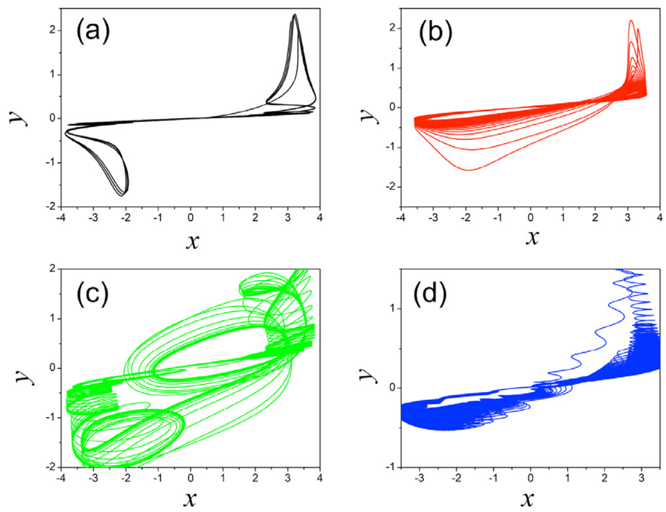

Fig. 6. Phase portraits between membrane potential and current in an isolate neuron by applying different frequency brand of external forcing current. For (a) $f_2 = 0.006$; (b) $f_2 = 0.06$; (c) $f_2 = 0.66$; (d) $f_2 = 6.66$. The time-varying electromagnetic field is considered as $\lambda_E = 1.0$, $\lambda_H = 1.0$, and $I_1 = I_2 = 6.0$, $f_1 = 0.06$.

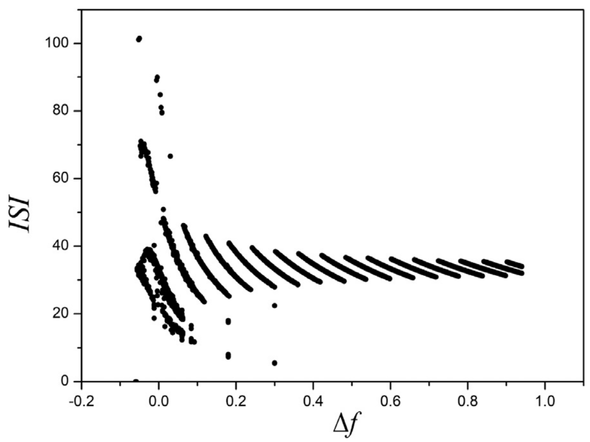

Fig. 7. Bifurcation diagram *ISI* (calculated from the time series for membrane potential of neuron) vs. frequency band Δf. The parameters are set as $I_1 = I_2 = 6.0$, $f_1 = 0.06$ and the electromagnetic field is not considered as $\lambda_E = 1.0$, $\lambda_H = 1.0$.

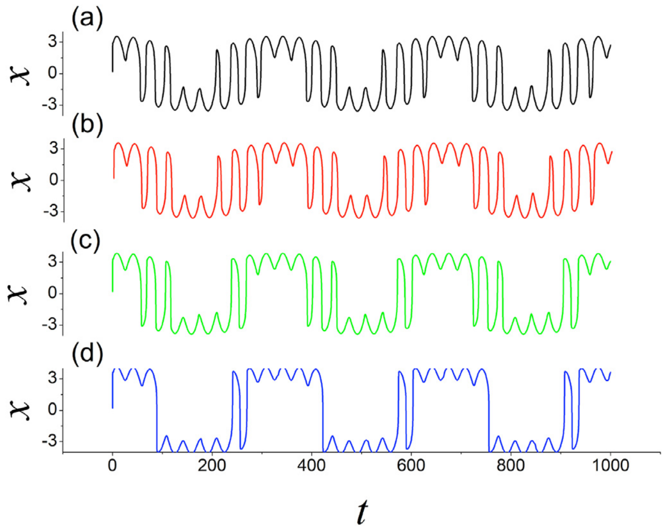

Fig. 8. Firing patterns of neural activities when the time-varying electromagnetic field is considered ($\lambda_E = 1.0$, $\lambda_H = 1.0$). For (a) $\alpha = 0.01$; (b) $\alpha = 0.1$; (c) $\alpha = 1.0$; (d) $\alpha = 2.0$ while another parameter in memristor is fixed at $\beta = 0.02$.

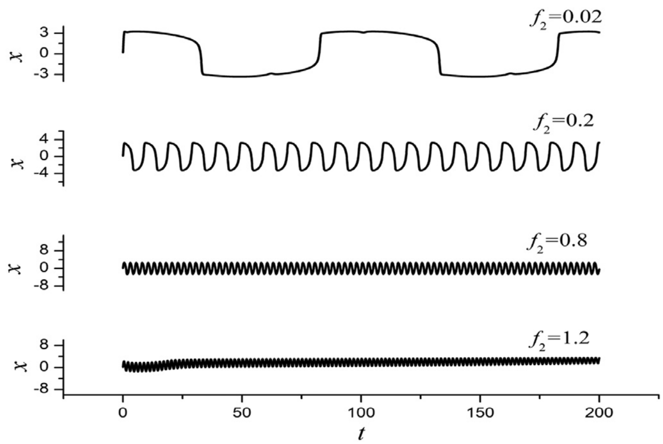

Fig. 9. Sampled time series of membrane potential in an isolate neuron by applying a single-channel external forcing current. For (a) $I_{ext} = 6\cos(f_2\pi t)$, $I_1 = 0.0$, $V_{th} = 0.0$; The parameters are fixed as $k_1 = 1.0$, $k_2 = 1.0$, $k_3 = 1.0$, $k_4 = 0.01$.

membrane potential due to its action on quadratic magnetic flux. Neurons can present quiescent, spiking, bursting [60] and even chaotic behaviors by applying appropriate stimulus. The firing pattern is much dependent on the excitability which can be adjusted by external forcing current. When the effect of electromagnetic field is considered, the electrical activities and firing pattern can also be modulated in effective way by generating induction current. As shown in Fig. 3, external electromagnetic radiation is switched on, and periodic stimulus is imposed via single channel, the electrical activities are calculated in Fig. 9.

From Fig. 9, it is confirmed that the electrical activities can be controlled to generate periodic oscillation when external forcing current is selected with different frequencies. To discern the effect of electromagnetic radiation, the external forcing current is fixed at $I_{ext} = 6\cos(0.2\pi t)$ while the electromagnetic radiation is tamed with different types of signals, and the results are plotted in Fig. 10.

It is found that periodic firing activities can be perturbed to generate intermittent firing series, and low frequency in the electromagnetic radiation can also be effective to suppress the electrical activities.

4. Circuit experiment of the neuron with electromagnetic field

It is interesting to verify these results on circuit platform, and the Multisium 14.0 tool is used for experimental verification. Then the analog circuit for the neuron model is designed and the schematic diagram for circuit is shown in Fig. 11.

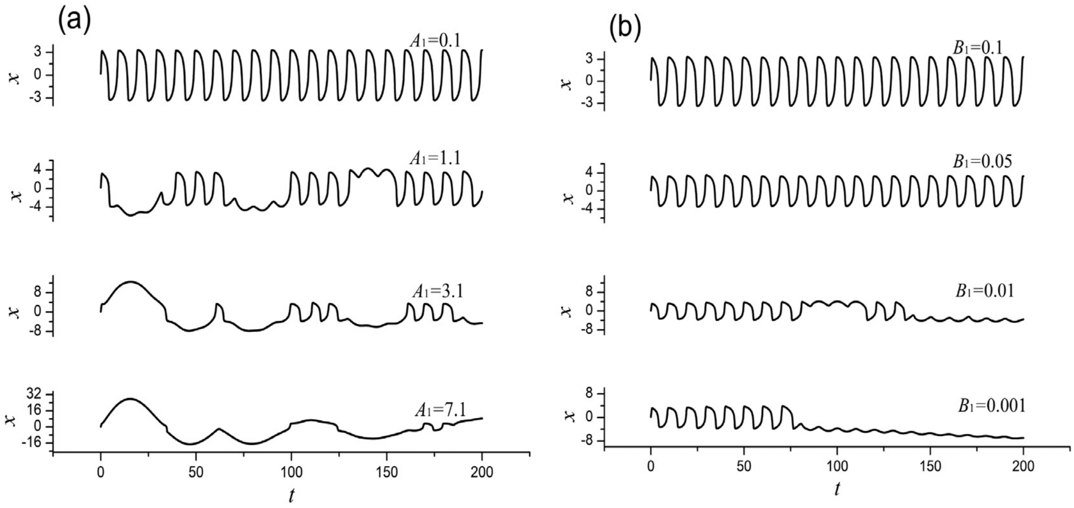

Fig. 10. Sampled time series of membrane potential in an isolate neuron by varying the amplitude (A_1) or frequency (B_1) in the external magnetic radiation at fixed $V_{th} = 1.0$, $A_0 = 0.01$. For (a) $A_2 = 0.1$, $B_1 = B_2 = 0.1$; (b) $A_1 = A_2 = 0.1$, $B_2 = 0.1$. The parameters are fixed as $k_1 = 1.0$, $k_2 = 1.0$, $k_3 = 1.0$, $k_4 = 0.01$.

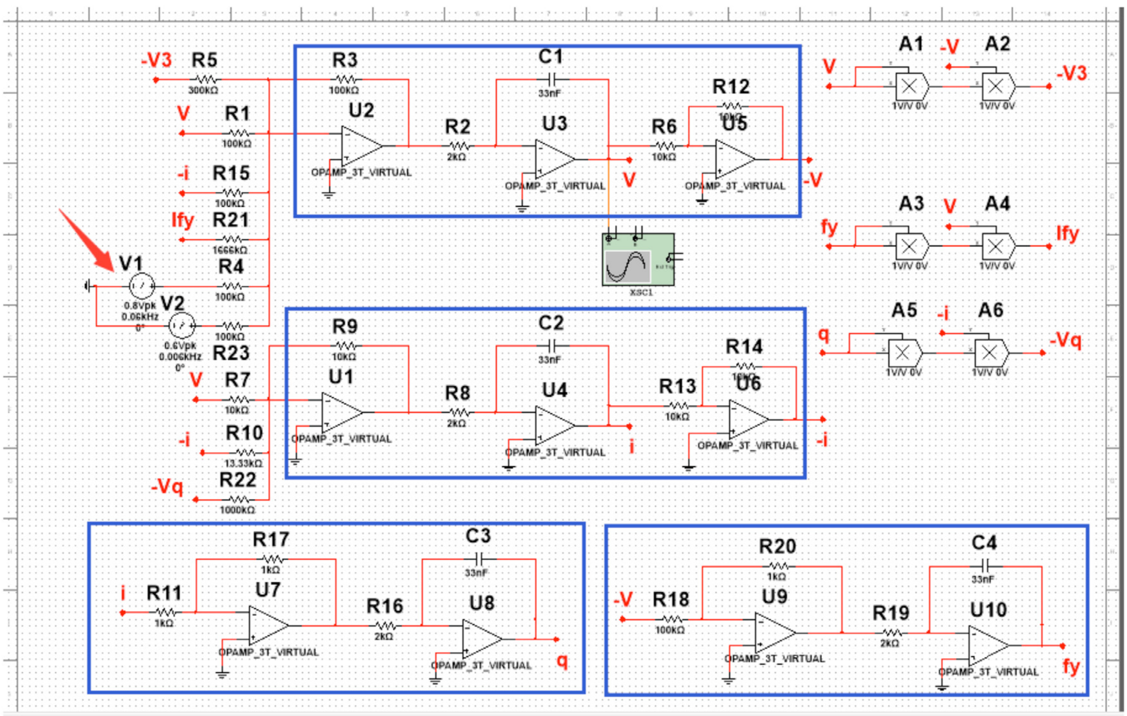

Fig. 11. Experimental schematic circuit.

For an isolate circuit, the external forcing current V1 and V2 are selected to generate different firing patterns. In Fig. 12, the outputs for voltages are calculated to observe the firing patterns over time series.

The experimental results (in Fig. 12) are in good agreement with the numerical simulations (in Fig. 8).

Also, the circuit parameters can be adjusted to trigger a variety of modes and transmission in electrical activities, and it can also describe the outputs response when electromagnetic radiation is applied. The parameter region in our proposed model has been extended by introducing more parameters thus the property of neuron and media can be considered. Furthermore, biological experiments can be practiced to give exact value for these dynamical parameters for nonlinear analysis. In fact, noise plays important role in regulating the nonlinear outputs in biological, physical and chemical systems. From physical view, the involvement of noise can input energy supply for the system even if the energy can't be absorbed completely. As a result, a variety of noise can be considered by adding multiple noise sources [61,62] on the systems. As

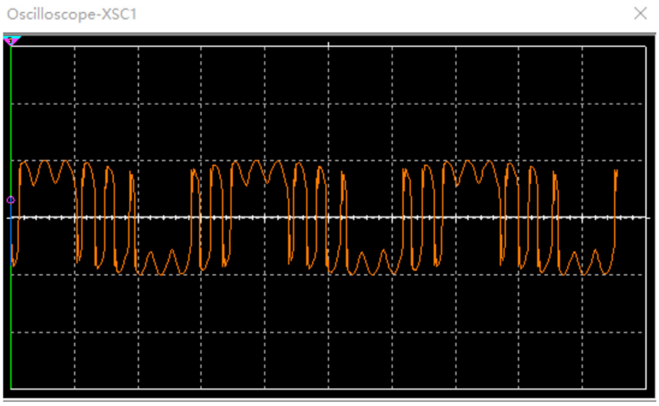

Fig. 12. Firing patterns for outputs voltage from the neuron circuit in presence of time-varying electromagnetic field.

mentioned above, neuron models can be used to discuss the effect of stochastic and coherence resonance in neuron and neural networks [63], and autaptic effect can also be considered by adding autapse connection to the neurons [64–66]. In fact, our presented neuron model can be further used to confirm the same discussion and investigation under noise, and network can also be built to detect the collective response and pattern selection as well.

5. Conclusions

A neuronal model, with time-varying electromagnetic field because of continuous ionic flux from dendrite to soma, is reconstructed. Electrical activities can be reproduced by basic components in analog circuit. In this paper, nonlinear electric devices such as charge-controlled memristor and flux-controlled memristor are used to describe the effect of time-varying electromagnetic field. Based on the principle of dimensional consistency, charge and magnetic flux are introduced into the neuronal model. The phase portraits can present the dependence relation between membrane potential and current, which is helpful to understand the electrical activities. It is found that the multi-scroll attractor can be triggered and also tamed when the time-varying electromagnetic field is considered. This new neuron model and circuit approach can describe the effect of electromagnetic field well and it may throw light on further investigation on network of circuits exposed to electromagnetic radiation.

Acknowledgments

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References

[1] A.L. Hodgkin, K. Bernard, The effect of sodium ions on the electrical activity of the giant axon of the squid, J. Physiol. 108 (1) (1949) 37–77.
[2] L.I. Zhang, M.M. Poo, Electrical activity and development of neural circuits, Nature Neurosci. 4 (2001) 1207–1214.
[3] R.W. Berry, Ribonucleic acid metabolism of a single neuron: correlation with electrical activity, Science 166 (3908) (1969) 1021.
[4] C. Demerens, B. Stankoff, M. Logak, et al., Induction of myelination in the central nervous system by electrical activity, Proc. Natl. Acad. Sci. 93 (18) (1996) 9887–9892.
[5] P. Pedarzani, J. Mosbacher, A. Rivard, et al., Control of electrical activity in central neurons by modulating the gating of small conductance Ca^{2+} activated K^{+} channels, J. Biol. Chem. 276 (13) (2001) 9762–9769.
[6] K. Grill-Spector, R. Henson, A. Martin, Repetition and the brain: neural models of stimulus-specific effects, Trends Cogn. Sci. 10 (1) (2006) 14–23.
[7] J.A. Anderson, Cognitive and psychological computation with neural models, IEEE Trans. Syst. Man Cybern. 5 (1983) 799–815.
[8] H. Gu, B. Pan, A four-dimensional neuronal model to describe the complex nonlinear dynamics observed in the firing patterns of a sciatic nerve chronic constriction injure model, Nonlinear Dyn. 81 (2015) 2017–2126.
[9] C. Wang, J. Ma, A review and guidance for pattern selection in spatiotemporal system, Int. J. Mod. Phys. B 32 (6) (2018) 1830003.
[10] G. Aston-Jones, S. Chen, Y. Zhu, et al., A neural circuit for circadian regulation of arousal, Nature Neurosci. 4 (7) (2001) 732.
[11] H. Adesnik, W. Bruns, H. Taniguchi, et al., A neural circuit for spatial summation in visual cortex, Nature 490 (7419) (2012) 226.
[12] W. Xu, T.C. Südhof, A neural circuit for memory specificity and generalization, Science 339 (6125) (2013) 1290–1295.
[13] C. Constantinidis, X.J. Wang, A neural circuit basis for spatial working memory, Neuroscientist 10 (6) (2004) 553–565.
[14] M. Kouh, T. Poggio, A canonical neural circuit for cortical nonlinear operations, Neural Comput. 20 (6) (2008) 1427–1451.
[15] L.E. Clarke, B.A. Barres, Emerging roles of astrocytes in neural circuit development, Nat. Rev. Neurosci. 14 (5) (2013) 311.
[16] J. Tang, J. Zhang, J. Ma, et al., Astrocyte calcium wave induces seizure-like behavior in neuron network, Sci. China Technol. Sci. 60 (2017) 1011–1018.
[17] P.G. Hadon, G. Carmignoto, Astrocyte control of synaptic transmission and neurovascular coupling, Physiol. Rev. 86 (3) (2006) 1009–1031.
[18] M. Zonta, M.C. Angulo, S. Gobbo, et al., Neuron-to-astrocyte signaling is central to the dynamic control of brain microcirculation, Nature Neurosci. 6 (1) (2003) 43.
[19] S. Guo, J. Tang, J. Ma, et al., Autaptic modulation of electrical activity in a network of neuron-coupled astrocyte, Complexity 2017 (2017) 4631602.
[20] D. Noble, Cardiac action and pacemaker potentials based on the Hodgkin-Huxley equations, Nature 188 (4749) (1960) 495.
[21] P. Bernardi, G. D'Inzeo, A generalized ionic model of the neuronal membrane electrical activity, IEEE Trans. Biomed. Eng. 41 (2) (1994) 125.
[22] D.T. Kaplan, J.R. Clay, T. Manning, et al., Subthreshold dynamics in periodically stimulated squid giant axons, Phys. Rev. Lett. 76 (21) (1996) 4074.
[23] W. Rall, Electrophysiology of a dendritic neuron model, Biophys. J. 2 (1962) 145.

[24] J. Nagumo, S. Sato, On a response characteristic of a mathematical neuron model, Kybernetik 10 (1972) 155–164.
[25] N. Kasabov, To spike or not to spike: A probabilistic spiking neuron model, Neural Netw. 23 (2010) 16–19.
[26] W. Gerstner, R. Naud, How good are neuron models? Science 326 (5951) (2009) 379–380.
[27] A.L. Hodgkin, A.F. Huxley, A quantitative description of membrane current and its application to conduction and excitation in nerve, J. Physiol. 52 (1-2) (1990) 25–71.
[28] J. Ma, L. Huang, J. Tang, et al., Spiral wave death, breakup induced by ion channel poisoning on regular Hodgkin–Huxley neuronal networks, Commun. Nonlinear Sci. Numer. Simulat. 17 (11) (2012) 4281–4293.
[29] X.J. Sun, X. Shi, Effects of channel blocks on the spiking regularity in clustered neuronal networks, Sci. China Technol. Sci. 57 (5) (2014) 879–884.
[30] G.R. Mirams, Y. Cui, A. Sher, et al., Simulation of multiple ion channel block provides improved early prediction of compounds' clinical torsadogenic risk, Cardiovasc. Res. 91 (1) (2011) 53–61.
[31] F.M. Dreyfus, A. Tscherter, A.C. Errington, et al., Selective T-type calcium channel block in thalamic neurons reveals channel redundancy and physiological impact of IT window, J. Neurosci. 30 (1) (2010) 99–109.
[32] H. Gu, B. Pan, G. Chen, et al., Biological experimental demonstration of bifurcations from bursting to spiking predicted by theoretical models, Nonlinear. Dyn. 78 (2014) 391–407.
[33] S. Majhi, M. Perc, D. Ghosh, Chimera states in a multilayer network of coupled and uncoupled neurons, Chaos 27 (2017) 073109.
[34] B.K. Bera, S. Majhi, D. Ghosh, et al., Chimera states: effects of different coupling topologies, Europhys. Lett. 118 (2017) 10001.
[35] V. Baysal, E. Yilmaz, Ö. Mahmut, Blocking of wave signal propagation via autaptic transmission in scale-free networks, Istanbul Univ. J. Electr. Electron. Eng. 17 (1) (2017) 3091–3096.
[36] X. Sun, G. Li, Synchronization transitions induced by partial time delay in an excitatory-inhibitory coupled neuronal network, Nonlinear Dyn. 12 (2017) 315–342.
[37] S.Y. Kim, W. Lim, Dynamical responses to external stimuli for both cases of excitatory and inhibitory synchronization in a complex neuronal network, Cogn. Neurodyn. 11 (5) (2017) 395–413.
[38] J. Ma, H.X. Qin, X.L. Song, et al., Pattern selection in neuronal network driven by electric autapses with diversity in time delays, Int. J. Mod. Phys. B 29 (2015) 1450239.
[39] Z. Rostami, S. Jafari, Defects formation and spiral waves in a network of neurons in presence of electromagnetic induction, Cogn. Neurodyn. 12 (2) (2018) 235–254.
[40] C. Wang, M. Lv, A. Alsaedi, et al., Synchronization stability and pattern selection in a memristive neuronal network, Chaos 27 (2017) 113108.
[41] G. Zhang, F.Q. Wu, T. Hayat, et al., Selection of spatial pattern on resonant network of coupled memristor and Josephson junction, Commun. Nonlinear Sci. Numer. Simulat. 65 (2018) 79–90.
[42] X.Y. Hu, C.X. Liu, L. Liu, et al., An electronic implementation for Morris–Lecar neuron model, Nonlinear Dyn. 84 (2017) 2317–2332.
[43] G. Ren, P. Zhou, J. Ma, et al., Dynamical response of electrical activities in digital neuron circuit driven by Autapse, Int. J. Bifurcat. Chaos 27 (2017) 1750187.
[44] X.Y. Wu, J. Ma, L.H. Yuan, et al., Simulating electric activities of neurons by using PSPICE, Nonlinear Dyn. 75 (2014) 113–126.
[45] M. Perc, Thoughts out of noise, Eur. J. Phys. 27 (2) (2006) 451.
[46] A.T. Barker, I.L. Freeston, R. Jalinous, et al., Magnetic stimulation of the human brain and peripheral nervous system: an introduction and the results of an initial clinical evaluation, Neurosurg 20 (1) (1987) 100–109.
[47] A.T. Barker, R. Jalinous, I.L. Freeston, Non-invasive magnetic stimulation of human motor cortex, Lancet 325 (8437) (1985) 1106–1107.
[48] M. Perc, M. Marhl, Amplification of information transfer in excitable systems that reside in a steady state near a bifurcation point to complex oscillatory behavior, Phys. Rev. E 71 (2005) 026229.
[49] S.S. Nagarajan, D.M. Durand, E.N. Warman, Effects of induced electric fields on finite neuronal structures: a simulation study, IEEE Trans. Biomed. Eng. 40 (11) (1993) 1175–1188.
[50] P.J. Basser, B.J. Roth, Stimulation of a myelinated nerve axon by electromagnetic induction, Med. Biol. Eng. Comput. 29 (3) (1991) 261–268.
[51] J.F. Barry, M.J. Turner, J.M. Schloss, et al., Optical magnetic detection of single-neuron action potentials using quantum defects in diamond, Proc. Natl. Acad. Sci. 113 (49) (2016) 14133–14138.
[52] M. Lv, C. Wang, G. Ren, et al., Model of electrical activity in a neuron under magnetic flow effect, Nonlinear Dyn. 85 (2016) 1479–1490.
[53] F. Wu, C. Wang, Y. Xu, et al., Model of electrical activity in cardiac tissue under electromagnetic induction, Sci. Rep. 6 (2016) 28.
[54] C.N. Takembo, A. Mvogo, H.P.E. Fouda, et al., Modulated wave formation in myocardial cells under electromagnetic radiation, Int. J. Mod. Phys. B 32 (14) (2018) 1850165.
[55] J. Ma, F. Wu, T. Hayat, et al., Electromagnetic induction and radiation-induced abnormality of wave propagation in excitable media, Physica A 486 (2017) 508–516.
[56] FitzHughR, Impulses and physiological states in theoretical models of nerve membrane, Biophys. J. 1 (1961) 445–466.
[57] F.W. Hu, B.C. Bao, H.G. Wu, et al., Equivalent circuit analysis model of charge-controlled memristor and its circuit characteristics, Acta Phys. Sin. 62 (21) (2013) 218401 in Chinese.
[58] Q.H. Hong, Y.C. Zeng, Z.J. Li, Design and simulation of chaotic circuit for flux-controlled memristor and charge-controlled memristor, Acta Physica Sin. 62 (23) (2013) 230502 in Chinese.
[59] Y. Wang, C.N. Wang, G.D. Ren, et al., Energy dependence on modes of electric activities of neuron driven by multi-channel signals, Nonlinear Dyn. 89 (2017) 1967–1987.
[60] X.L. Yang, J.Y. Wang, Z.K. Sun, The collective bursting dynamics in a modular neuronal network with synaptic plasticity, Nonlinear Dyn. 89 (2017) 2593–2602.
[61] I. Franović, K. Todorović, M. Perc, et al., Activation process in excitable systems with multiple noise sources: One and two interacting units, Phys. Rev. E 92 (2015) 062911.
[62] M. Uzuntarla, M. Ozer, U. Ileri, et al., Effects of dynamic synapses on noise-delayed response latency of a single neuron, Phys. Rev. E 92 (2015) 062710.
[63] E. Yilmaz, V. Baysal, M. Ozer, Enhancement of temporal coherence via time-periodic coupling strength in a scale-free network of stochastic Hodgkin–Huxley neuron, Phys. Lett. A 379 (2015) 1594–1599.
[64] E. Yilmaz, M. Ozer, V. Baysal, et al., Autapse-induced multiple coherence resonance in single neurons and neuronal networks, Sci. Rep. 6 (2016) 30914.
[65] E. Yilmaz, V. Baysal, M. Ozer, et al., Autaptic pacemaker mediated propagation of weak rhythmic activity across small-world neuronal networks, Physica A 444 (2016) 538–546.
[66] E. Yilmaz, V. Baysal, M. Perc, Enhancement of pacemaker induced stochastic resonance by an autapse in a scale-free neuronal network, Sci. China Technol. Sci. 59 (3) (2016) 364–370.