A novel digital circuit for astrocyte-inspired stimulator to desynchronize two coupled oscillators

Conference Paper · November 2014

DOI: 10.1109/ICBME.2014.7043898

1 author:

Soheila Nazari
Amirkabir University of Technology

A Novel Digital Circuit for Astrocyte-Inspired Stimulator to Desynchronize Two Coupled Oscillators

Soheila Nazari
Department of Electrical Engineering
Amirkabir University of Technology
Tehran, Iran

Karim Faez
Department of Electrical Engineering
Amirkabir University of Technology
Tehran, Iran

Mahmood Amiri *
Medical Biology Research Center,
Kermanshah University of Medical Sciences
Corresponding author- ma.amiri@ece.ut.ac.ir

Ehsan Karami
Department of Electrical Engineering
Razi University
Kermanshah, Iran.

Abstract-Pathophysiologic neural synchronization is a sign of several neurological disorders such as parkinson and epilepsy. In addition, based on established neurophysiologic findings, astrocytes (more type of glial cells) regulate dynamically the synaptic transmission and have key roles in stabilizing neural synchronization. Therefore, in the present study, a new model for digital astrocyte-inspired stimulator is proposed and constructed to break the synchronous oscillations of a minimal network. The minimal network is composed of two Hopf oscillators connected via gap-junction. The complete digital circuit of the closed loop system that is the proposed astrocyte-inspired stimulator and the coupled Hopf oscillators are implemented in hardware on the ZedBoard development kit. The results of MATLAB, ModelSim simulations and FPGA implementations confirm that the digital proposed astrocyte-inspired stimulator can effectively desynchronize the synchronous oscillations of the coupled Hopf oscillator with a demand-controlled characteristic. In this way, the designed digital stimulator not only does not suppress oscillator natural features but also it successfully maintains the desired asynchronous activity.

Keywords: Astrocyte, Synchronization, FPGA, DBS,

1. Introduction

Synchronization is a well-known phenomenon of collective dynamics of interacting oscillators. Many applications of synchronization have been found in physics, engineering, biology, and neuroscience [1]. In normal brain function, neural synchronization is supposed as an important mechanism for information processing and signaling [2,3]. On the other hand, a sign of several neurological diseases such as Parkinson's disease or epilepsy is excessive synchronized discharges of neurons [4]. Deep brain stimulation (DBS) is a successful clinical treatment for patients with medically robust neurological diseases[5]. Recently, a feedback-based DBS has been tested in primate model of Parkinson disease [6] and a rodent model of epilepsy [7]. In addition to DBS, other ways for elimination of synchrony have been recommended in literature [8,9,10].
The analog VLSI implementation of neural network in silicon [11] offers high computational power at the expense of flexibility and design iteration times [12]. Therefore, it is necessary to have a rapid prototyping platform for neural models with similar flexibility to general goal microprocessors. Field-programmable gate arrays hardware (FPGA) is an complete technology to achieve these terms [13]. Flexibility, digital precision, and stability are interesting features of FPGAs for designing neuromorphic systems. These devices are fast, can be reprogrammed easily and provid large numbers of individual circuit elements which are parallel and may be configured arbitrarily [14].
Recent experimental findings confirm the functional contribution of *astrocytes* in neural synchronization [3,15,16] and their abilities to regulate and stabilize the neural activities by providing appropriate feedback [17]. Motivated by this, in the current research a new digital hardware platform of the astrocyte-inspired stimulator to desynchronize a coupled Hopf oscillator is presented. We use two coupled Hopf oscillators to create a minimal model since the Hopf oscillator is the normal form of a regular periodic oscillation. Similar to [18,9,19] the astrocyte-inspired stimulator is a dynamic stimulator. It takes the state variables of the oscillators as the input and then produces appropriate stimulation signal to break the network synchrony. We use the astrocyte mathematical model proposed by [20] which is a simplified version of the astrocyte functional-biophysical model developed by [21]. We have implemented a functional approach for the closed loop system and develop not only a digital circuit for astrocyte dynamics as the bio-inspired stimulator but also for the two coupled Hopf oscillators as well. The open loop (coupled Hopf oscillators) and the closed loop system (astrocyte-inspired stimulator with the coupled Hopf oscillators) are first simulated in MATLAB. Next, the designed digital circuits for the open and close loop systems are simulated in ModelSim and finally they are implemented in hardware using ZedBoard development kit. The results of the FPGA implementation are in agreement with those of ModelSim and MATLAB simulations and verify that an astrocyte-inspired stimulator could be a candidate as a new DBS technique.
The rest of this paper is organized as follows: The dynamics of the original and proposed stimulator model and open and close loop systems are explained in Section 2 and their digital circuits are described in Section 3. The MATLAB, ModelSim simulations and FPGA implementations are presented in Section 4. Also, the performance of the

proposed digital circuits for the astrocyte-inspired stimulator is evaluated. Finally, Section 5 concludes the paper.

2. The minimal network

A. Oscillators model

In this section, we first present the dynamic model of the Hopf oscillator, two coupled oscillators, then mathematical description of the original and proposed astrocyte model as a bio-inspired stimulator and finally the closed loop system is explained.

To create the minimal network the Hopf oscillator is used which described by:

$$x_i' = x_i - \omega_i y_i - x_i(x_i^2 + y_i^2) \quad i = 1,2 \tag{1}$$

$$y_i' = \omega_i x_i + y_i - y_i(x_i^2 + y_i^2) \quad i = 1,2 \tag{2}$$

where x_i ,$y_i$are the oscillators state variablesand the oscillation frequency is ω_i, i=1,2, $\omega_1 \neq \omega_2$.

For simplicity in the digital circuit and eliminating the use of multiplier in circuit design we use mathematical modification of Hopf oscillator in [22] that described by:

$$x_i' = [1 - (|x_i| + |y_i|)]sgn(x_i) + \omega_i y_i \quad i = 1,2 \tag{3}$$

$$y_i' = [1 - (|x_i| + |y_i|)]sgn(y_i) - \omega_i x_i \quad i = 1,2 \tag{4}$$

In the remaining of the paper we use Eqs (3,4) for the Hopf oscillators.

Next, we create a minimal model (open loop system) which is consisted of two Hopf oscillators, coupled through *gap junctions*. The mathematical descriptions of two coupled oscillator are as follows:

$$x_i' = [1 - (|x_i| + |y_i|)]sgn(x_i) + \omega_i y_i + c(x_k - x_i)$$
$$i, k \in \{1,2\}, \mathrm{i} \neq \mathrm{k} \tag{5}$$

$$y_i' = [1 - (|x_i| + |y_i|)]sgn(y_i) - \omega_i x_i + c(y_k - y_i)$$
$$i, k \in \{1,2\}, \mathrm{i} \neq \mathrm{k} \tag{6}$$

where C is the coupling strength. Increase in C leads to enhancement of the coupling strength between oscillators and also influences their synchrony.

B. Dynamics of the original and proposed stimulator

The dynamics of the original stimulator is described by the following set of differential equations:

$$q' = (1 + tanh[k_4(Z - k_5)])(1 - q) - k_6 q \tag{7}$$

$$p' = -k_1 p + k_2 + k_3 q \tag{8}$$

where q is the stimulator internal state and represents the production of secondary messenger within the astrocyte, p is the stimulator output which denotes the mediator released by the astrocyte, Z is the stimulator input and models the interaction between astrocyte and nearby neurons and finally k_i , i=1,2,…6 are stimulator parameters which are positive constants. The two-way communication between stimulator and oscillators is defined with the parameter Z (stimulator input) that is $Z = a * \sum_{i=1}^{2}(x_i + y_i)$ where $a>0$ is an amplifying parameter.

Table I: The parameter values of stimulator taken from Montaseri et al (2011)

Parameter	value	Parameter	value	Parameter	value
k_1	1	k_2	0.05	k_3	1.5
k_4	1	k_5	2	k_6	2

In this work for efficiently low-cost hardware implementation on digital platforms and eliminating the use of multiplier in circuit design we proposed a new model for stimulator. One of the main challenges in digital implementation of the astrocyte-inspired stimulator is the presence of the nonlinear *q-nullcline* in the form of *tanh(.)*function. One of the method is to use a look up table to approximate this nonlinear function which needs many comparators and several registers for the memory space. Another method is to use the linear approximation method and try to approximate the *tanh(.)* function of the stimulator dynamical system with several line segments which decreases the implementation cost significantly [23] but in this way we can not eliminating the use of multiplier in digital circuit design so to achieve this goal we use the surface fitting with least squares approximation method .In this method we try to approximate surface with linear equations. We have Eq (11) in the stimulator equations

$$q' = y = (1 + tanh[k_4(Z - k_5)])(1 - q) - k_6 q \tag{9}$$

We want to have Eq (10) instead of Eq (9)

$$q' = aZ + bq + c \tag{10}$$

For obtain coefficient of linear Eq (10) the surface y divided into four parts and we choose 30000 random point on each part. For example for obtain coefficient in Eq (10) we solve follow equations

$$\begin{bmatrix} z_1 & p_1 & 1 \\ z_2 & p_2 & 1 \\ & . & \\ & . & \\ & . & \\ z_{30000} & p_{30000} & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_{30000} \end{bmatrix} \sim AX = B \tag{11}$$

For solve Eq (11)

$$(A^T A)X = A^T B \quad \rightarrow \quad X = (A^T A)^{-1}(A^T B) \tag{12}$$

With solve the above equation we obtain coefficient of linear Eq (10). So the proposed model for stimulator is as follow:

$$\mathrm{p}' = -p + 1.5q + 0.05 \tag{13}$$

$$\mathrm{q}' = aZ + bq + c \tag{14}$$

coefficients of linear Eq (14) denoted in table II

Table II: Coefficients of linear equations

Region of Z	Region of q	a	b	C
Z≤0.6	q <0.25	0.0106	-2.009	0.0228
0.6<Z<2.9	q <0.25	0.2172	-2.1401	-0.001
Z≥2.9	q <0.25	0.7765	-2.8737	-0.5628
Z<4	0.25<q<0.5	0.01	-2	0.023

To implement above equations in digital circuit we use the SCM technique and modify the coefficient constants so that they can be rewrite based on the power of 2. In this way we obtain the following coefficients for linear equation 14 according to table III.

Table III: Coefficients of linear equation with SCM technique for digital implementation

Regionof Z	Region of q	a	b	c
Z≤0.6	q <0.25	0.0156	-2	0.02343
0.6<Z<2.9	q <0.25	0.25	-2.25	-0.0109
Z≥2.9	q <0.25	0.75	-3	-0.5
Z<4	0.25<q<0.5	0.0156	-2	0.023

C. The close loop system

The stimulator work on the observation *Z* of the oscillators' states and produce an helpful control input (*p*). A scaled version of this stimulator output ($\lambda_i.p$) is feedback to the individual oscillators. In this way, to implement the interaction of the bio-inspired stimulator with neighboring neurons "$+\lambda_i.p$"and "-$\lambda_i.p$"is added to Eqs (5,6). In this way, the scheme of the closed-loop system consists of two coupled oscillators and stimulator which is shown in Fig.1, is described as:

$$x_1' = [1-(|x_1|+|y_1|)]sgn(x_1)+\omega_1 y_1 + c(x_2-x_1)+\lambda_1 p \qquad (15)$$
$$y_1' = [1-(|x_1|+|y_1|)]sgn(y_1)-\omega_1 x_1 + c(y_2-y_1)+\lambda_1 p \qquad (16)$$

$$x_2' = [1-(|x_2|+|y_2|)]sgn(x_2)+\omega_2 y_2 + c(x_1-x_2)-\lambda_2 p \qquad (17)$$
$$y_2' = [1-(|x_2|+|y_2|)]sgn(y_2)-\omega_2 x_2 + c(y_1-y_2)-\lambda_2 p \qquad (18)$$

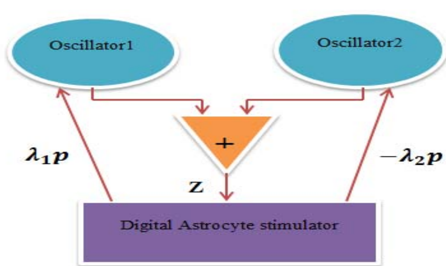

Fig. 1. The general scheme of the closed-loop system. It composed of two coupled oscillators and a bio-inspired stimulator. The stimulator applied control signal $\lambda_i.p$ based on the oscillators' state *Z*.

3. Hardware Implementation

Whereas digital computation utilizes more silicon area and power per function than its analog counterpart, it has additional advantages. Low cost, flexibility, availability and digital precision are interesting features that favor FPGAs a promising substitute to analog VLSI based approaches for designing neuromorphic systems [24,14].

In this section, we present a digital framework which can be implemented on low-cost and widely available hardware platforms such as FPGAs. Since the closed loop system is composed of two coupled oscillators and the astrocyte-inspired stimulator. For digital implementation, the original continuous time dynamical equations of the Hopf oscillator are discretized using Euler method which is simple and produces acceptable responses. The discrete equations for the closed loop system is as follows:

$$x_1[n+1] = \big[[1-(|x_1[n]|+|y_1[n]|)]sgn(x_1[n]) + \omega_1 y_1[n] + c(x_2[n]-x_1[n]) + \lambda_1 p[n]\big]h + x_1[n] \qquad (19)$$
$$y_1[n+1] = [[1-(|x_1[n]|+|y_1[n]|)]sgn(y_1[n]) - \omega_1 x_1[n] + c(y_2[n]-y_1[n]) + \lambda_1 p[n]\,]h + y_1[n] \qquad (20)$$
$$x_2[n+1] = \big[[1-(|x_2[n]|+|y_2[n]|)]sgn(x_2[n]) + \omega_2 y_2[n] + c(x_1[n]-x_2[n]) - \lambda_2 p[n]\big]h + x_2[n] \qquad (21)$$
$$y_2[n+1] = [[1-(|x_2[n]|+|y_2[n]|)]sgn(y_2[n]) - \omega_2 x_2[n] + c(y_1[n]-y_2[n]) - \lambda_2 p[n]\,]h + y_2[n] \qquad (22)$$
$$\mathrm{p}[n+1] = [-p[n] + 1.5q[n] + 0.05]h + p[n] \qquad (23)$$
$$\mathrm{q}[n+1] = [aZ[n] + bq[n] + c]h + q[n] \qquad (24)$$

where *h* is discretizing step and in our design is set to 0.0625. We try to use the minimum required resources to design the digital circuit to reduce the digital implementation cost and to achieve this goal we proposed a new approximation for stimulator and SCM technique to implemented close loop system with minimum required resources and without use of multipliers. Here, we limit to have only five adders in the arithmetic unit (AU). The scheduling diagram for astrocyte-stimulator is demonstrated in Fig 2. It should be pointed out that this proposed hardware is composed of ADD or comparison and thus the hardware implementation cost has been reduced, significantly. The resource utilization of the FPGA implementations is summarized in Table IV.

Table IV. Low-level device utilization summary

Slice Logic Utilization	Used	Available	Utilization
Number of Slice LUTs	866	53200	1%
Number of bonded IOBs	740	106400	1%
Number of Slice Registers	830	53200	1%

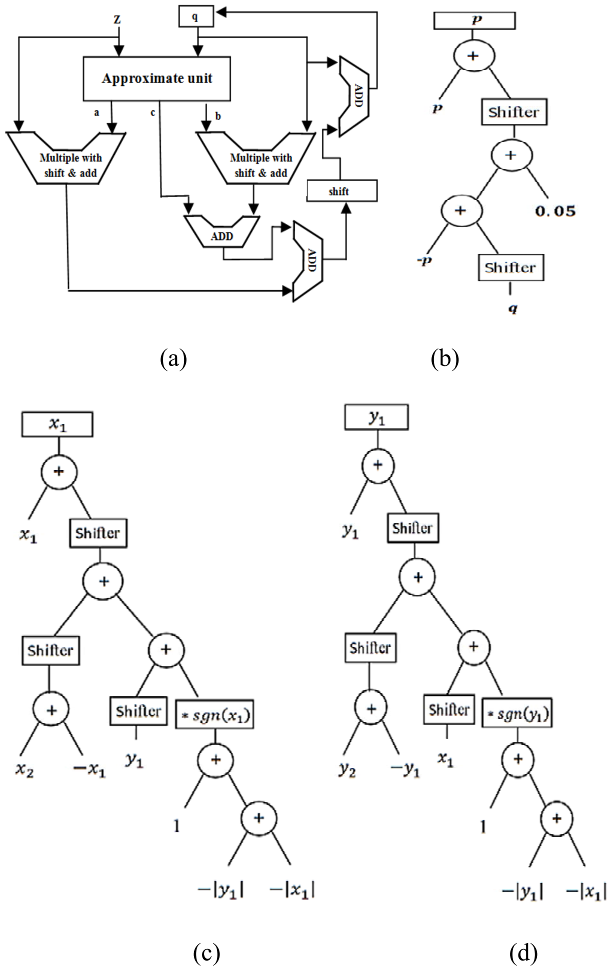

Fig. 2. The scheduling diagram of the system. (a) the *q*-dynamic. (b) the *p*-dynamic.(c) the x_1 dynamic.(d) the y_1 dynamic.

4. Results of simulations and hardware implementation

In this section, the results of the open and closed loop system both in simulation and in hardware are presented. We discuss how the astrocyte-inspired stimulator can break the synchronous oscillation of the minimal network.In the openloop system stimulator receive the state of the oscillators with the parameter Z and dont give any feedback to the system.first panel in fig.3(a) shows the natural oscillation of the two oscillators for the open loop system when both oscillators oscillated with the same frequency $\omega_1 = \omega_2 = 0.1$ and second panel show output of stimulator in Matlab. first panel of fig3(b) shows oscillation of two oscillator with the equal frequancy in Modelsim and second panel show the output of stimulator in Modelsim.the RMSE between Matlab and Modelsim result is 0.1651.

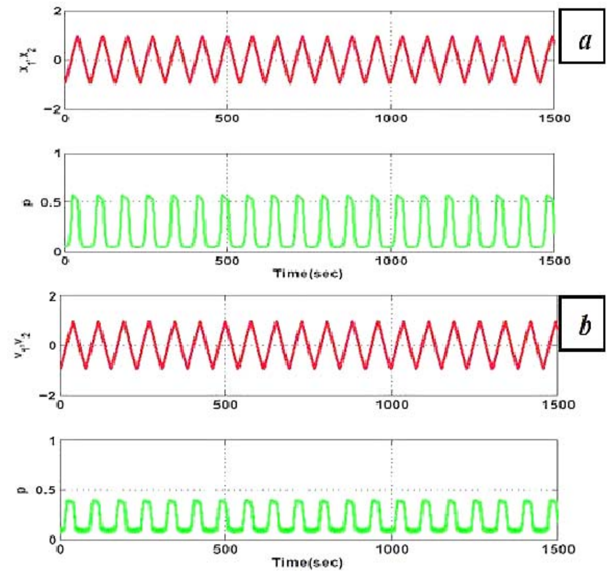

Fig. 3. Oscillation of the two oscillator with the same frequancy(first panel) and output of stimulator (second panel) in (a) Matlab simulation and (b) Modelsim simulation.

In the open loop system when two oscillator oscillate with different frequancy ($\omega_1 = 0.1, \omega_2 = 0.11$) we have figure 4. First panel of fig.4(a) show the oscillation of two oscillator and second panel show the output of stimulator in Matlab. First panel of fig.4(b) show the oscillation of the stimulator and second panel show output of stimulator in Modelsim simulation. The RMSE between Matlab and Modelsim result is 0.1665.

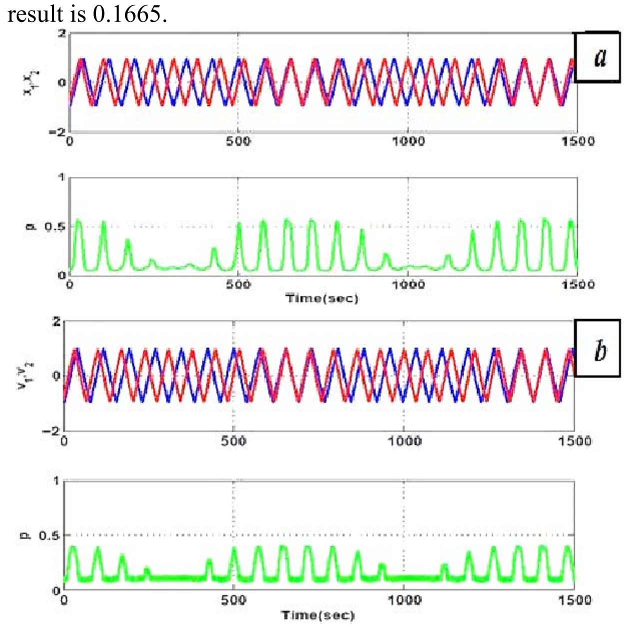

Fig. 4. Oscillation of the two oscillator with the different frequency (first panel) and output of stimulator (second panel) in (a) Matlab simulation and (b) Modelsim simulation.

Next, we consider the closed loop system in which the astrocyte-inspired stimulator is also considered. Results of

MATLAB simulations for the closed loop system with original model for stimulator and Results of Modelsim simulations for the closed loop system with proposed model for stimulator are depicted in Fig. 5. Fig5(a) show matlab simulation and Fig.5(b) show Modelsim simulation and the top panel in Fig.5(a),(b) shows the enhancement of coupling level, *C*, the middle panel shows the oscillations of the coupled Hopf oscillators. The third panel is stimulation signal which is applied by the astrocyte-inspired stimulator to the individual oscillators. In other words, the third panel shows the stimulator output (*p*). For the simulations shown in Fig. 5, λ_1 = 0.01 and λ_2 = 0.005. We investigate the performance of the digital stimulator by turning ON and OFF intermittently. The results are depicted in Fig.5(a) (Matlab simulation for the closed loop system with original model for stimulator) and Fig.5(b)(Modelsim simulation for the closed loop system with proposed model for stimulator). As can be observed, as the stimulator switch off, the two coupled oscillators get synchronized as the coupling strength is high. However, as the stimulator switch on again, the asynchronous activity appears and reveals that the astrocyte-inspired stimulator could be a candidate as a new DBS technique.

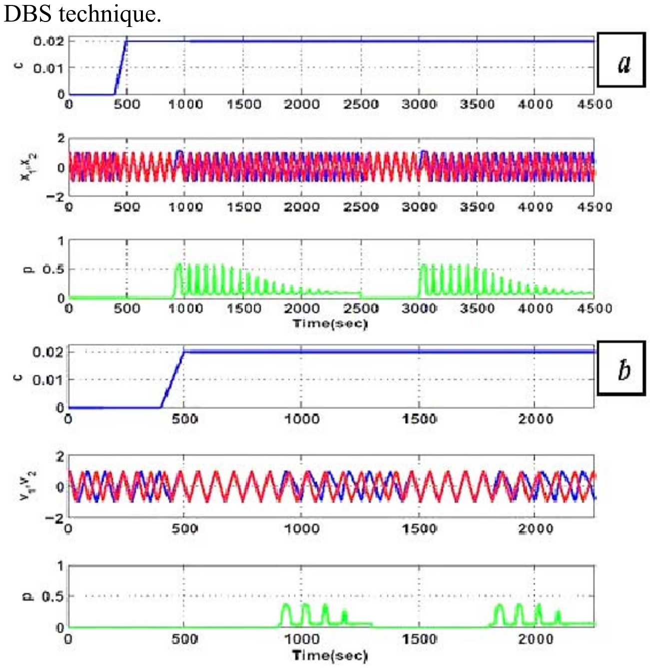

Fig.5. (a) shows The Matlab simulation results of the closed loop system(in 0<t<900sec and 2500<t<3000sec stimulation is OFF and for 900<t<2500sec and 3000<t<4500sec stimulation is ON) (b) shows the Modelsim simulation results.(for 0<t<900sec and 1300<t<1800sec, stimulation is OFF and for 900<t<1300sec and 1800<t<2300sec stimulation is ON).

From the fig.5 we can show that the new model for stimulator can effectively desynchronize the synchronous oscillations of the coupled Hopf oscillator and have efficiently low-cost hardware implementation on digital platforms without need of multiplier For digital implementation. The implemented digital stimulator desynchronizes the two Hopf oscillators without any inappropriate effects on the intrinsic characteristics of oscillators. Indeed, it does not change the amplitude of oscillations and does not make the oscillators to stop, eliminate or start different oscillations. Moreover, it has a demand controlled characteristic which means that it adaptively achieve the desynchronization. Therefore, the amplitude of stimulation signal vanishes as the oscillators become desynchronized. In this way, the astrocyte-inspired stimulator generates the appropriate stimulations so that when the coupled oscillator become desynchronized, the input (*Z*) gets close to zero and this leads to a reduction in the stimulator output (*p*). To evaluate the performance of the digital circuit in hardware, it has been implemented on a ZedBoard development kit. The primary objective is to examine the feasibility of FPGA implementation of the model and to show that hardware can reproduce the model responses. Fig. 6 displays oscilloscope photographs of the close loop system implementation. Fig.6(a) shows the output of the two coupled oscillators when the coupling strength is high enough, that the two coupled oscillators get synchronized. Fig.6(b) shows the output of the two oscillator when they are asynchron with applying stimulator.

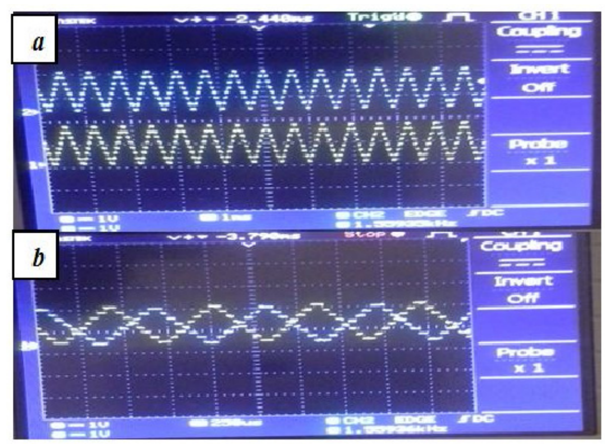

Fig.6. The results of hardware implementation of the designed digital circuit.

5. Conclusion

Although, in normal brain function, the neural synchronization plays an important role in information processing, excessive synchronous neuronal activity is a sign of several neurological disorders such as parkinson and epilepsy [25]. Indeed this pathophysiologic neuronal synchronization causes the Interference normal function of the brain. In these situations, DBS is a appropriate tool involving the implantation of a medical device which injects electrical impulses to the brain, although its basic principles and mechanisms are still vague [5].

Considering recent theoretical and neurophysiologic researchs, it is accepted that astrocytes dynamically set the synaptic transmission of neuronal networks and have a primary role in stabilizing neural activities [26,27]. In this way, an astrocyte-inspired stimulator was proposed by the [20]. In this paper, we continue this line of research and proposed a digital circuit for this bio-inspired stimulator to be implemented in hardware. In addition, a digital circuit for the minimal network consisted of two coupled Hopf oscillators was proposed. Thus, the complete digital circuit of the close loop system that is the astrocyte-inspired stimulator and the coupled Hopf oscillators were implemented in hardware on the FPGA ZedBoard development kit. The results of MATLAB, ModelSim simulations and FPGA implementations verified that the developed digital circuit for the astrocyte-inspired stimulator can effectively desynchronize the synchronized coupled Hopf oscillators and it has two main advantages: First, the stimulator is able to break the synchronous oscillations of the coupled Hopf oscillators without suppressing the oscillations, changing the amplitude or starting divergent oscillations. Second, it has a “demand-controlled” characteristic and desynchronizes the minimal network by applying low amplitude stimulation signal and maintain the desired asynchronous activities.

References

[1] C. A. S.Batista , S. R. Lopes , R. L.Viana and A. M. Batista. "Delayed feedback control of bursting synchronization in a scale - free neuronal network." *Neural Networks*, vol. 23, no. 1, pp.114-124, 2010.

[2] L.M. Ward. " Synchronous neural oscillations and cognitive processes ." *Trends in cognitive sciences.* vol. 7, no. 12, pp. 553-559, 2003.

[3] M.Amiri, N.Hosseinmardi, F.Bahrami, M.Janahmadi. " Astrocyte-neuron interaction as a mechanism responsible for generation of neural synchrony : a study based on modeling and experiments". *Journal of computational neuroscience.* vol. 34, no. 3 ,pp. 489-504, 2013.

[4] J.De Keyser, J. P.Mostert, M. W.Koch. " Dysfunctional astrocytes as key players in the pathogenesis of central nervous system disorders. " *Journal of the neurological sciences.*vol. 267, no. 1, pp.3-16, 2008.

[5] M . L. Kringelbach , N . Jenkinson , S . L . Owen, T. Z . Aziz, " Translational principles of deep brain stimulation." *Nature Reviews Neuroscience. v*ol. 8, no. 8, pp. 623-635, 2007.

[6] B.Rosin, et al. " Closed-loop deep brain stimulation is superior in ameliorating parkinsonism." *Neuron.*vol. 72, no. 2, pp. 370-384, 2011.

[7] A.Berényi, M.Belluscio, D.Mao, G.Buzsáki. " Closed-loop control of epilepsy by transcranial electrical stimulation." *Science.*vol. 337, no. 6095, pp. 735-737, 2012.

[8] C.Hauptmann, O. Popovych, P. A. Tass. " Demand - controlled desynchronization of oscillatory networks by means of a multisite delayed feedback stimulation."*Computing and Visualization in Science* .vol. 10, no. 2, pp. 71-78, 2007.

[9] M.Luo, Y.Wu, J. Peng." Washout filter aided mean field feedback desynchronizationin an ensemble of globally coupled neural oscillators ." *Biological cybernetics.*vol. 101, no. 3, pp. 241-246, 2009.

[10] O.V.Popovych, P. A.Tass."Synchronization control of interacting oscillatory ensembles by mixed nonlinear delayed feedback." *Physical Review E.*vol. 82, no. 2, pp. 026204, 2010.

[11] G.Indiveri, T. K.Horiuchi."Frontiers in neuromorphic engineering ." *Frontiers in neuroscience.*vol. 5, 2011.

[12] J. H. Wijekoon , P. Dudek . " VLSI circuits implementing computational models of neocortical circuits." *Journal of neuroscience methods.*vol. 210, no. 1, pp. 93-109, 2010.

[13] K.L.Rice, et al. " FPGA implementation of Izhikevich spiking neural networks for character recognition." *International Conference on* IEEE, pp. 451-456, 2009.

[14] W. X.Li , et al. " Real - Time Prediction of Neuronal Population Spiking Activity Using FPGA. " *Biomedical Circuits and Systems, IEEE Transactions.* vol. 7, no. 4, pp. 489-498, 2013.

[15] M.Amiri, F.Bahrami, M.Janahmadi. " Functional contributions of astrocytes in synchronization of a neuronal network model". *Journal of theoretical biology.* vol. 292, pp.60-70, 2012.

[16] M.Amiri, G.Montaseri, F.Bahrami. " On the role of astrocytes in synchronization of two coupled neurons: a mathematical perspective. " *Biological cybernetics*, vol. 105, no. 2, pp.153-166, 2011.

[17] T.Fellin. " Communication between neurons and astrocytes: relevance to the modulation of synaptic and network activity." *Journal of neurochemistry.* vol. 108, no. 3, pp.533-544, 2009.

[18] N.Tukhlina, M.Rosenblum. " Feedback suppression of neural synchrony in two interacting populations by vanishing stimulation." *Journal of biological physics.* vol. 34, no. 3-4, pp. 301-314, 2008.

[19] G.Montaseri, M .J.Yazdanpanah, A.Pikovsky , M.Rosenblum, " Synchrony suppression in ensembles of coupled oscillators via adaptive vanishing feedback." *Chaos : An Interdisciplinary Journal of Nonlinear Science.* vol. 23, no. 3, 2013.

[20] G.Montaseri, M. J.Yazdanpanah, M, Amiri. " Astrocyte - inspired controller design for desynchronization of two coupled limit - cycle oscillators." In *Nature and Biologically Inspired Computing (NaBIC), 2011 Third World Congress on IEEE*, pp. 195-200, 2011.

[21] D. E.Postnov, et al. "Dynamical patterns of calcium signaling in a functional model of neuron–astrocyte networks." *Journal of biological physics.* vol.35, no. 4, pp. 425-445, 2009.

[22] A.Ahmadi, et al. " On the VLSI implementation of adaptive-frequency hopf oscillator. " *Circuits and Systems I: Regular Papers, IEEE Transactions.* vol. 58, no. 5, pp. 1076-1088, 2011.

[23] S.Nazari, K.Faez, E.Karami, M.Amiri. " A Digital Neurmorphic Circuit for a Simplified Model of Astrocyte Dynamics ". *Neuroscience letters*, vol. 582, pp. 21-26, 2014.

[24] R.Guerrero - Rivera , T. C. Pearce. " Attractor – based pattern classification in a spiking FPGA implementation of the olfactory bulb." *Neural Engineering. CNE'07. 3rd International Conference on.* IEEE, 2007.

[25] M.Amiri, F.Bahrami, M.Janahmadi. " On the role of astrocytes in epilepsy:a functional modeling approach". *Neuroscience research.* vol. 72, no. 2, pp. 172-180, 2012.

[26] N. B. Hamilton, D. Attwell. " Do astrocytes really exocytose neurotransmitters?. " *Nature Reviews Neuroscience.* vol. 11, no. 4, pp. 227-238, 2010.

[27] M.A.Di Castro, et al. " Local Ca2+ detection and modulation of synaptic release by astrocytes. " *Nature neuroscience,*vol. 14, no. 10, pp. 1276-1284, 2011.