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Synchronization of Two Chau's Oscillator's Using Current Conveyor (Ccii+) in Matlab Simulink

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Research Article

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ABSTRACT

Introduction: A synchronization of two Chua's oscillator's, which exhibits chaotic behaviour is presented in various circuits. This new realization consists of the Current Conveyor (CCII+) based circuit, and is in parallel with the nonlinear resistor. A synchronization of two Chua's oscillator using Current Conveyor (CCII+) is presented.

Method: Master/Slave coupling between two Chua's oscillators for state v1, v2, v3, and v4 is easily achievable with just two resistors and one-second current conveyors. As stated earlier, there is an alternative construction for the main block of Chau's circuit model in Simulink. It is constructed by using gain block, absolute blocks, adding, and constant blocks. System state variables v1, v2 andiLare represented at the output of integrator blocks. A Simulink model for Chau's circuit with the piecewise-linear nonlinear function. The circuit is realized by differential (voltage to current) pairs feeding two capacitors, which carry the dynamics, with the key component being a (voltage to current) binary hysteresis circuit due to Linares. Chau's oscillator realized with the commercially available positive-type second-generation Current Conveyor (CCII+) is included in the TL802 or AD844 device.

Result: Simulated results for two synthetic values of inductance L1=18mH and L2=10 mH are presented. It can be monitored as time-domain response and v1- v2 phase portrait illustrations in SIMULINK. Chua's circuit may work in equilibrium region, period-n limit region, chaotic region or saturation region. In the synchronization of Chua's circuit, the synchronization behavior is more sensitive to R0 mismatch than L and C mismatch, as it decides the chaotic behaviour of the circuit. In sound synthesis application, interesting sounds are synthesized with Chua's circuit.

Application: The proposed circuits find applications in many areas such as secure communication, medical field, fractal theory, and Sound synthesis.

INTRODUCTION

A current conveyor based Chua's oscillator was presented by Sanchez LC [1]. The current conveyor is a four device which when arranged with other electronic elements in specific circuit configurations can perform many useful analog signal processing functions [2]. In many ways, the current conveyor simplifies circuit design in much the same manner as the convection operational amplifier. Chua's circuit has been widely used because it allows the development of new designs and applications [3-6]. Chua's circuit is one of the most investigated chaotic oscillators which consists of a third-order linear part composed of two grounded capacitors, a grounded inductor and a resistor along with a nonlinear negative resistor popularly known as Chua's diode. The architecture of this oscillator is based on coupling a tank resonator (parallel L-C_2) to an active three-segment voltage-controlled nonlinear resistor (Chua's diode) through a filter (R-C_1). A realization of the nonlinear resistor by connecting two voltage-controlled negative impedance converters in parallel has been accepted. Chaos phenomenon is usually observed in dynamic systems that are especially sensitive to initial conditions [4]. Different from linear systems, the chaos system is an extremely nonlinear system where a little change in initial (present) conditions can greatly change the output.

Chaos can be used for signal processing. Since little change in an initial condition can greatly change output, it is extremely useful for encryption and communication. With Chaos signal processing, the initial condition is very hard to be estimated for attackers which only have output conditions. This enables efficient encryption and secure communication. Adaptive synchronization of Chua's oscillators can be categorized into two parts, adapting the control coupling between the two circuits [7-11] and adapting one or more parameters of the Chua's oscillators. Both adaptive synchronization approaches have been digitally implemented for secure communication applications. However, little work has been studied in the Synchronization of two Chau's oscillators using the Current Conveyor (CCII+). since the CFOA consists of a positive-type second-generation Current Conveyor (CCII+) in cascade connection with a voltage follower [9], then this work is oriented to show the usefulness of the CCII+ to realize a current conveyor based on two synchronized Chua's oscillator. Hence, Chua's diode is realized by using two Current Conveyors (CCII+) in Senani R [3], while the simulated inductance is realized by using four Current Conveyors (CCII+). The design of the current conveyor at the transistor level of abstraction can be revised in Sedra A [11]. Synchronization of two Chau's oscillators using current conveyor is easy to design, due to the absence of inductor. Simulation can be performed using MATLAB Simulink.

LITERATURE REVIEW

CMOS implementable current conveyors and CMOS implementable analog functions using them so that they can be easily implemented in CMOS technology [12-16].CMOS technology is used for CCII implementation. In this circuit diagram, as well as elsewhere subsequently, the various MOS current mirrors and MOS current repeaters are shown by their standard symbolic notations consisting of two or more circles touching each other with connection to positive/negative power supply rail (s), with input terminal shown with an arrow mark and the terminal (s) without arrow mark being the output terminal (s). For the current conveyor CCII, the one basic topology can be used. The first of them is based on the second one that uses the operational amplifier feedback structure. They have some advantages and some worse properties as well, of course. In contrast to that, the feedback of the operational amplifier structure copies the voltage from input Y to the input X and at the same time guarantees a very low impedance at the input X node. The current from the input X is then conveyed by the transistors M_5, M_6, M_{11}, M_{12} and corresponding current mirrors M_7, M_8, M_9, M_{10} to the output Z in the show circuit the "push-pull" transistor branches were used. In this circuit, it can be observed that MOSFETs M_5-M_6 and M_7-M_8 represent, respectively, current repeater and current mirror. The basic core of the circuit consists of transistors $M_1$and M_2 and the transistors M_1-M_2 as well M_3-M_4 as well-matched such that $\dfrac{\left(\frac{W(\mu m)}{L(\mu m)}\right)_1}{\left(\frac{W(\mu m)}{L(\mu m)}\right)_2} = \dfrac{\left(\frac{W(\mu m)}{L(\mu m)}\right)_3}{\left(\frac{W(\mu m)}{L(\mu m)}\right)_4}$. It can beseen that the drain currents of M_1 and M_2 are identical so that V_{GS1} and V_{GS2} will cancel out each other and as a consequence, V_x=V_y will be attainable [14]. It can be observed that the source current ofM_1 and the drain current of M7 are equal and will force I_y=0. On the other hand, with I_1=I_2, the node equation at node Z will yield I_z=I_x. Using operational amplifier topology the current conveyor, regarding the Y-terminal voltage can be designed. The highest disadvantage appears the possibility to reach maximum current conveyor gain bandwidth comparable with operational amplifiers for the technology is used **(Table 1)**.

Table 1. Simulated parameter of conveyors CCII designed in CMOS technology.

Parameter	CCII- operational amplifier structure
Power Supply voltage	± 1.5
Max output current I_{outmax}	± 1.5
The systematic current offset between I_x and I_z	4 nA
Matching current offset between I_x and I_z	3 μA at 1 σ
Systematic voltage offset between V_x and V_y	100 μV
Matching voltage offset between V_x and V_y	2 mV at 1 σ
GBW	1 MHz

In Chua's diode implementation using two CCII+ and four resistors (analogous to the one devised by Gandhi G [16] and simulating inductance circuit using only CCII+ elements and requiring a bare minimum of only three passive components namely two resistors and a grounded capacitor. All the current conveyors realize from AD844 this circuit exhibits a double scroll attractor for the following component values and bias voltages. CCII+1 biased with +5 V and CCII+2 biased with 12 V, the values of resistors as R_1=22 Ω, R_2=2.2 KΩ, R_3=22 KΩ, R_4=3.3 KΩ, R_{L1}=R_{L2}=13.4 Ω, C=C_1=10 nF, C_2=100nF,and R=180Ω.

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The chaos theory and Chua's circuit was introduced in Gaurav G, Chua LO, Kennedy MP, Matsumoto T, Matsumoto T, Elwakil AS, Xuan TT [16-22]. Chaos theory is mainly studied in physics, and mathematics, studying the system behaviour that is highly dependent on initial conditions. This effect is known as the butterfly effect. In chaos theory, the butterfly effect is the sensitive dependency on initial conditions in which a small change at one place in a deterministic nonlinear system can result in large differences in a later state. Lorenz created a simple set of equations which produce complicated dynamical object known as Lorenz attractor. Various inductors free Chua's circuit was available and the simple one is using resistor-capacitor network instead of the inductor. Active- resistors capacitor (R-C) sinusoidal oscillator is used to replace inductor-capacitor (L-C) tank circuit in Chua's circuit. Senani-Gupta realized the first successful implementation of synchronization of two Chau's oscillators using a current conveyor.

LITERATURE SURVEY

The current conveyor CCII was introduced by SedraA [5] as the new more versatile circuit against the older CCI. The operation of the CCII current conveyor is such that if the Current conveyor (CCII+) is constructed by a Voltage Follower (VF) between the Y-terminal and the X-terminal to accomplish $v_x=v_y$, and a Current Mirror (CM) between the X-terminal and the Z-terminal to accomplish $i_z=i_x$. The voltage at the X-terminal follows the same one applied to the Y-terminal, thus the X-terminal exhibits a zero input impedance. The current supplied to the X-terminal is conveyed to the high output impedance at the Z-terminal [5,12]. The mixed-mode characteristic of the CCII+ is exploited to implement the Chua's diode and the simulated inductor in straight form. The Chua's diode is implemented by two current conveyors and four resistors. The simulated inductance is implemented by four current conveyors and two resistors and one capacitor in **Figure 1**.

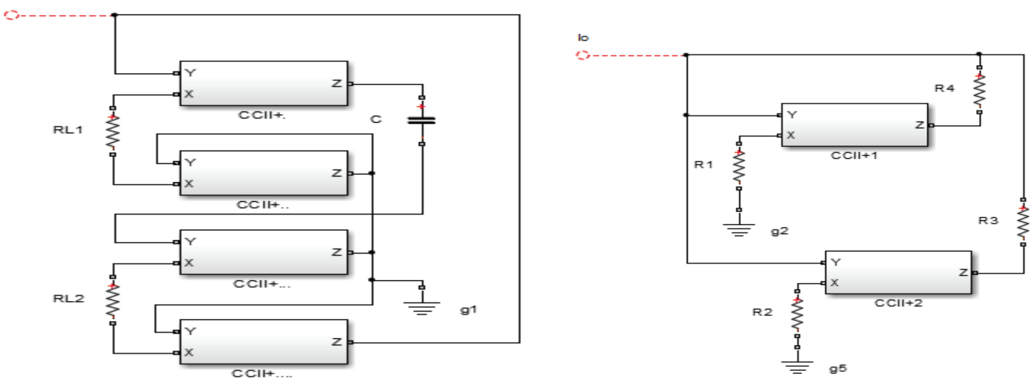

Figure 1. (a): simulated inductance in CCII+; (b):chua's diode in CCII+.

MATHEMATICAL MODEL

Chua's circuit is a simple oscillator circuit which exhibits a variety of bifurcation and chaos. The circuit contains three linear energy storage elements (an inductor and two capacitors), linear resistors and a single nonlinear resistor. Synchronization of a Chua's oscillator includes L as a linear inductor, R and R_0 as linear resistors, C_1,and C_2 as linear capacitors, and others that correspond to the Chua's diodes. Circuits providing mathematic operations: The Second Generation Current Conveyor is called CCII. CCII was characterized by the hybrid matrix

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix}$$

Given the above description, this three-port building block can be characterized by the following instantaneous relationships between its various port variables:

$i_x=i_z, v_x=v_y$ and $i_y=0$ (1)

Since CCII has ideally zero input impedance at its X-terminal when its Y-terminal is grounded, there will be virtual ground at the X-terminal. This makes it extremely simple to enable the submission of several current inputs at virtually grounded X-terminal. Furthermore, the output current I_0 is available from a high output impedance Z-terminal. CCII was a versatile building block capable of realizing several basic functions with the least possible number of external passive components. It was demonstrated in Smith KC and SedraA [5,11] that CCII was, indeed, a versatile building block for realizing many basic functions needed for analog computation such as current amplifier, current differentiator, current integrator, current summer, weighted current summer and generalized nonlinear function generator- all employing only a bare minimum number of passive components.

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The current conveyor CCII allows us to develop a large set of circuits realizing many of mathematic operations in classical voltage mode and current mode signal processing as well. Realizations of the most used operations by circuits using CCII+, including the corresponding transfer function, are introduced in **Figure 2**.

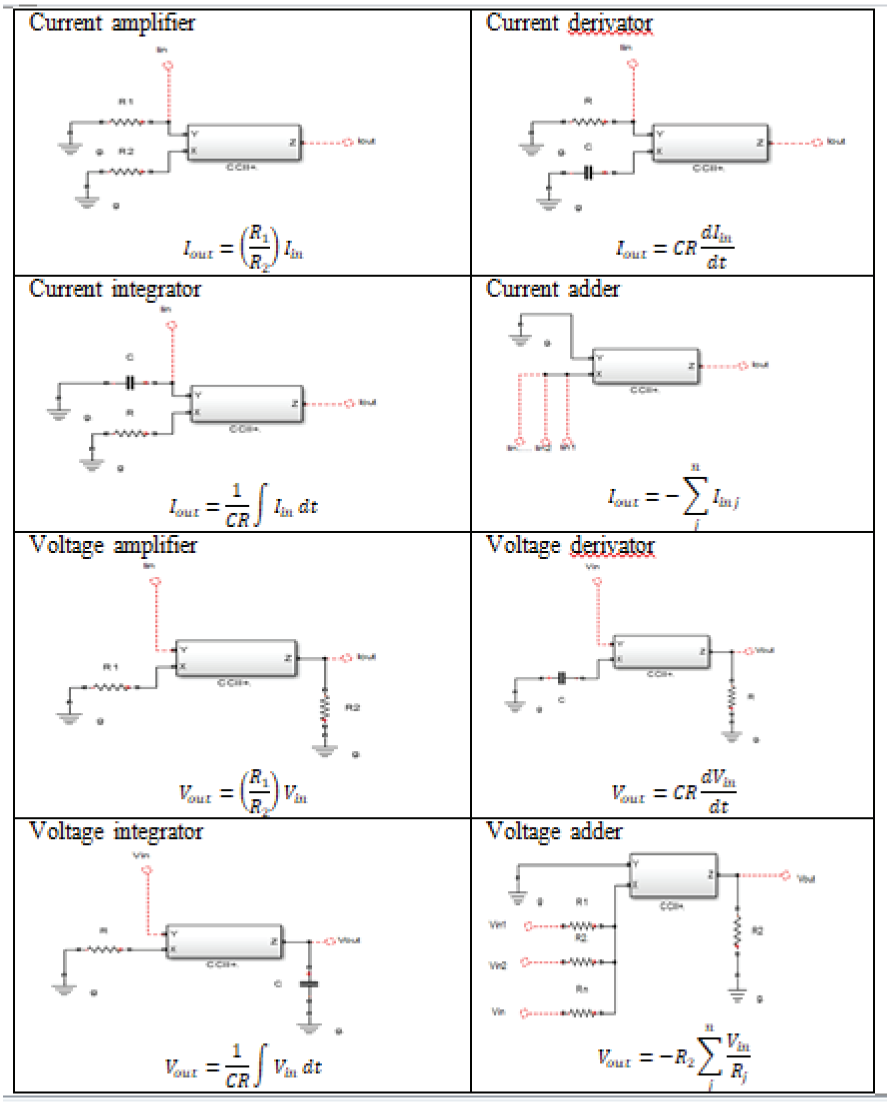

Figure 2. Mathematic operations realized by CCII.

CIRCUIT CONSTRUCTION

In this section, the mixed-mode characteristic of the CCII+ is exploited to implement the Chua's diode and the simulated inductor in straight form. An important issue is that this realization allows integrated circuit design. The construction of the chaotic circuit is shown in **Figure 3**.

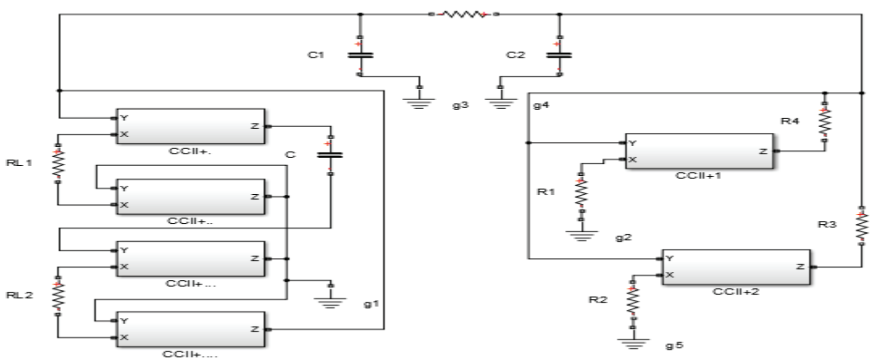

Figure 3. Current conveyors based realization of Chua's oscillator.

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p-ISSN:2347-2316

These make use of passive elements and active elements. Two Topologies that exist in literature are considered for analysis. The Mathematical analysis of various Topologies is as follows:

This topology employs 4 Second Generation Current Conveyors (CCII) and 3 passive elements. CCII+ is a three-port device in which the voltages on and currents through the various input-output terminals satisfy the following characteristics. From equation

$i_x=i_z$,$v_x=v_y$ and $i_y=0$

The simulated inductance is implemented by four CCII+s (L_1 to L_4), two resistors (R_{L1} andR_{L2}) and one capacitor (C_L).

Let the applied input voltage is v_{in}. Apply KCL at the input node,

I_{z1}, Current through R_{L1}, is

$$I_{z1}=\frac{V_{y1}-V_{x2}}{R_{L1}}$$

Where $V_{x2}=V_{y2}=0$ and $V_{x1}=V_{y1}$.

$$I_{z1}=\frac{V_{x1}}{R_{L1}} \qquad (2)$$

Apply KVL in the loop formed between ground of CCII+2, R_{L1},C and ground of CCII+3.

$I_{z1}=sCV_{x3}$ (3)

I_{z4}, Current through R_{L2}, is

$$I_{z4}=\frac{V_{y3}-V_{x2}}{R_{L2}}$$

where $V_{y2}=V_{x2}=0$ and $V_{x3}=V_{y3}$

$$I_{z4}=\frac{V_{y3}}{R_{L2}} \qquad (4)$$

Substituting equation (2), (4) into equation (3)

$I_{z1}=sCV_{x3}$

$V_{x1}=sCI_{z4}\ R_{L1}\ R_{L2}$

Where $V_{y1}=sLI_{z4}$

$L=CR_{L2}R_{L1}$ (5)

This topology employs 2 Second Generation Current Conveyors (CCII) and 4 passive elements. CCII+ is a three-port device in which the voltages on and currents through the various input-output terminals Equation (1). Chua's diode is implemented by two CCII+ (1 and 2) and four resistors (R_1, R_2, R_3 and R_4).

Let the applied input voltage is v_{in}. Apply KVL in the loop formed between the ground of CCII+1, R_1, $R_{2,}$ and ground of CCII+2.

I_{z1}, Current through R_1, is

$$I_{x1}=\frac{V_{y1}}{R_1}=\frac{V_{z1}}{R_4}$$

Where $V_{x1}=V_{y1}$ and $I_{x1}=I_{z1}$

$$I_{z1}=\frac{V_{x1}}{R_1}=\frac{V_{z1}}{R_4} \qquad (6)$$

I_{z2}, Current through R_2, is

$$I_{x2}=\frac{V_{y2}}{R_2}=\frac{V_{z2}}{R_3}$$

Where $V_{x2}=V_{y2}$ and $I_{x2}=I_{z2}$

$$I_{z2}=\frac{V_{x2}}{R_2}=\frac{V_{z2}}{R_3} \qquad (7)$$

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p-ISSN:2347-2316

From equation (6) and (7)

$$E_1 = \frac{R_1 E_{sat}}{R_4} \text{ and } E_2 = \frac{R_2 E_{sat}}{R_3}$$

Where $E_{sat}= V_{z2}=V_{z1}$, $E_1=V_{x1}$, $E_2=V_{x2}$, $G_{12}=-1/R_4$; $G_{02}=1/R_1$; $G_{01}=1/R_2$ and $G_{11}=-1/R_3$;

$G_a=G_{12}+G_{11}$

$G_b=G_{02}+G_{01}$

The first CCII+ based implementation of Chua's circuit uses a piecewise-linear function,

$$g(v_R) = G_b v_R + \frac{1}{2}(G_a - G_b)\{|v_R + E_1| - |v_R - E_1|\}$$

The nonlinear voltage-current (v-i) characteristic of the Chua's diode described as:

$$g(v_R) = \begin{cases} G_b v_R + (G_b - G_a) E_{min} & if\ v_R \le -E_{min} \\ G_a v_R & if\ |v_R| < E_{max} \\ G_b v_R + (G_a - G_b) E_{max} & if\ v_R \ge E_{max} \end{cases} \quad (8)$$

When taking the nonlinear resistor portion of the circuit as a single component, deriving the equations of state for the entire system becomes a rather simple exercise in Kirchhoff's laws and the mathematical relationships between voltage, current, and inductance:

For node 1, Using Kirchhoff's current law (KCL). We get

$$\frac{v_2 - v_1}{R} = c_1 \frac{dv_1}{dt} + g(v_1)$$

For node 2, Using Kirchhoff's current law (KCL). We get

$$\frac{v_1 - v_2}{R} = c_2 \frac{dv_2}{dt} - i_L \quad (9)$$

For node 3, Using Kirchhoff's voltage law (KVL). We get

$$v_2 = -L \frac{di_L}{dt} - i_L R_0$$

METHODS

The implementations of Chua's oscillators have been developed [23]. Simple nonlinear circuits may exhibit such chaotic behavior, the analysis and design of electronic circuits that generate chaotic signals have received great importance in recent years. Most of the chaotic signal generators proposed in the literature contain inductors, which is inconvenient for various reasons. Inductors are prepared separately in most applications. Compared to other circuit elements they are not ideal and they are bigger unless the inductance is rather small. An Inductorless design is also used for V_{LSI} implementation. Master/Slave coupling between two Chua's oscillators for state v_1, v_2, v_3, and v_4 is easily achievable with just two resistors and one CCII+ **(Figure 3)**. Where the simulated inductance of A is implemented by four CCII+s (L_1 to L_4), two resistors (R_{L1} and R_{L2}) and one capacitor (C_L), Chua's diode of A is implemented by two CCII+(1 and 2) and four resistors (R_1, R_2, R_3 and R_4). The simulated inductance of B is implemented by four CCII+s (L_1 to L_4), two resistors (RL_1 andRL2) and one capacitor (C_L). chua's diode of B is implemented by two CCII+(1 and 2) and four resistors (R_1, R_2, R_3 and R_4).

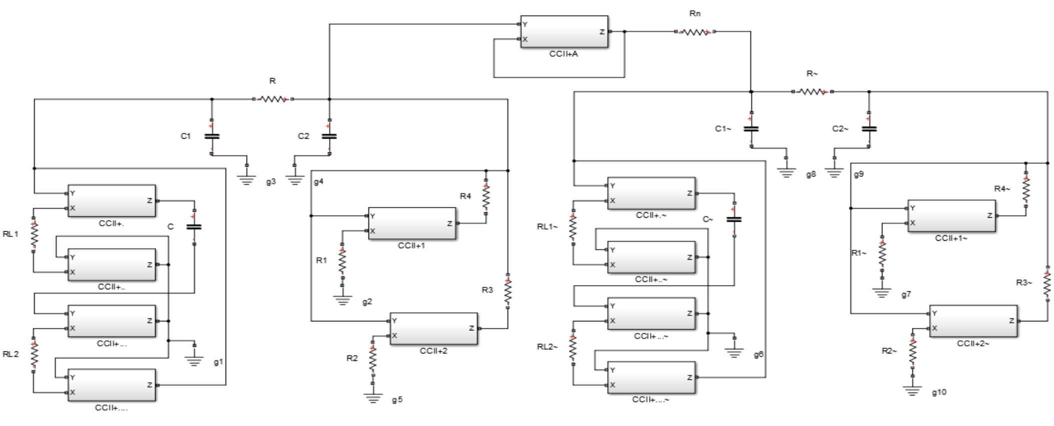

Figure 4. Current conveyors based realization of two Chua's oscillator.

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We consider a system consisting of two unidirectional coupled identical Chua's circuits from a master Chua's oscillator to a slave Chua's oscillator such that the slave Chua's oscillator synchronizes its states to the states of the master oscillator which operates autonomously. This configuration is shown in **Figure 4** where it is assumed that the following parameters of the master and slave Chua's oscillators are matched, R˜=R, (R)˜$_0$=R$_0$, C˜$_1$=C$_1$, and C˜$_2$=C$_2$.

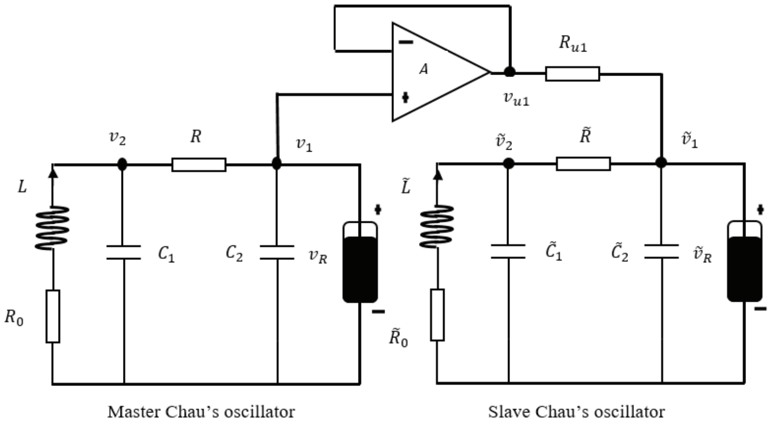

Figure 5. Master/slave Chau's oscillators.

Applying Kirchoff's law, the Chua's circuit is described by six differential equations:

For node 1, Using Kirchhoff's current law (KCL). We get

$$\frac{v_2 - v_1}{R} = c_1 \frac{dv_1}{dt} + g(v_1)$$

For node 2, Using Kirchhoff's current law (KCL). We get

$$\frac{v_1 - v_2}{R} = c_2 \frac{dv_2}{dt} - i_L$$

For node 3, Using Kirchhoff's voltage law (KVL). We get

$$v_2 = -L \frac{di_L}{dt} - i_L R_0 \qquad (10)$$

For node 4, Using Kirchhoff's current law (KCL). We get

$$\frac{\tilde{v}_2 - \tilde{v}_1}{\tilde{R}} = \tilde{c}_1 \frac{d\tilde{v}_1}{dt} + g(\tilde{v}_1) + \frac{(v_{u1} - \tilde{v}_1)}{R_{u1}}$$

For node 5, Using Kirchhoff's current law (KCL). We get

$$\frac{\tilde{v}_1 - \tilde{v}_2}{\tilde{R}} = \tilde{c}_2 \frac{d\tilde{v}_2}{dt} - \tilde{i}_L$$

For node 6, Using Kirchhoff's voltage law (KVL). We get

$$\tilde{v}_2 = -L \frac{d\tilde{I}_L}{dt} + \tilde{R}_0 \tilde{i}_L$$

Where voltage across capacitor C$_1$ is v$_1$, voltage across capacitor C˜$_1$ is v˜$_1$, current across inductor L is i$_L$, current across inductor L˜ is i˜$_L$ and g(v$_R$) nonlinear function defined by

$$g(v_R) = G_b v_R + \frac{1}{2}(G_a - G_b)\{|v_R + E_1| - |v_R - E_1|\} \qquad (11)$$

WhereE$_1$denotes the normalized breakpoint and segment slopes are denoted by G$_a$ and G$_b$. Computer simulations or by physical electronic implementations are used to study Chua's equation Chaoticbehaviour can be improved by using a resistor in series to inductor. By the use of larger energy storage elements can slow down chaotic oscillations.

The nonlinear voltage current (v-i) characteristic of the Chua's diode described as

$$g(v_R) = \begin{cases} G_b v_R + (G_b - G_a)E_1 & if\ v_R \le -E_1 \\ G_a v_R & if\ |v_R| < E_1 \\ G_b v_R + (G_a - G_b)E_1 & if\ v_R \ge E_1 \end{cases} \quad \text{and}$$

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p-ISSN:2347-2316

$$g\left(\tilde{v}_R\right)=\begin{cases} G_b\tilde{v}_R+\left(G_b-G_a\right)E_1 & if\ \tilde{v}_R\le -E_1 \\ G_a\tilde{v}_R & if\ \left|\tilde{v}_R\right|<E_1 \\ G_b\tilde{v}_R+\left(G_a-G_b\right)E_1 & if\ \tilde{v}_R\ge E_1 \end{cases}$$

Where G_a, G_b and E_1 are known real constants that satisfy $G_b<G_a<0$ and $E_1>0$

The state equations of the master and slave Chua's oscillators are given as

$$\frac{dv_1}{dt}=\frac{1}{C_1}\left(G\left(v_2-v_1\right)-g\left(v_1\right)\right) \quad (12)$$

$$\frac{dv_2}{dt}=\frac{1}{C_2}\left(G\left(v_1-v_2\right)+i_L\right) \quad (13)$$

$$\frac{di_L}{dt}=\frac{1}{L}\left(-v_2-R_0i_L\right) \quad (14)$$

$$\frac{d\tilde{v}_1}{dt}=\frac{1}{C_1}\left(G\left(\tilde{v}_2-\tilde{v}_1\right)-g\left(\tilde{v}_1\right)+G_{u1}\left(v_{u1}-\tilde{v}_1\right)\right) \quad (15)$$

$$\frac{d\tilde{v}_2}{dt}=\frac{1}{\tilde{C}_2}\left(G\left(\tilde{v}_1-\tilde{v}_2\right)+\tilde{i}_L\right) \quad (16)$$

$$\frac{d\tilde{I}_L}{dt}=\frac{1}{\tilde{L}}\left(-\tilde{v}_2-R_0\tilde{i}_L\right) \quad (17)$$

Where v_1 is the voltage over the capacitor c_1, v_2 is the voltage over the capacitor c_2, i_L is the current through the inductance, C is capacitance the capacitor, L is inductance the inductor, R_0 is resistance the linear resistor, $v^{\sim}_1$ is the voltage over the capacitor c_1, $v^{\sim}_2$ is the voltage over the capacitor $c^{\sim}_2$, $i^{\sim}L$ is the current through the inductance, $C^{\sim}$ is capacitance the capacitor, $L^{\sim}$ is inductance the inductor, $R^{\sim}_0$ is resistance the linear resistor, G is conductance the linear resistor ($G\triangleq 1/R$),$G^{\sim}$ is conductance the linear resistor ($G\triangleq 1/R^{\sim}$), $v_{u1}=v_1$ since it is the output of a voltage follower op-amp and $G_{u1}$is the conductance of the coupling resistor ($G_{u1}\triangleq 1/R_{u1}$) **(Figure 5)**.

Master and Slave Chua's oscillator of course Simulink is not limited to equations in one variable. Consider the Master and Slave Chua's oscillator in **Figure 6**.

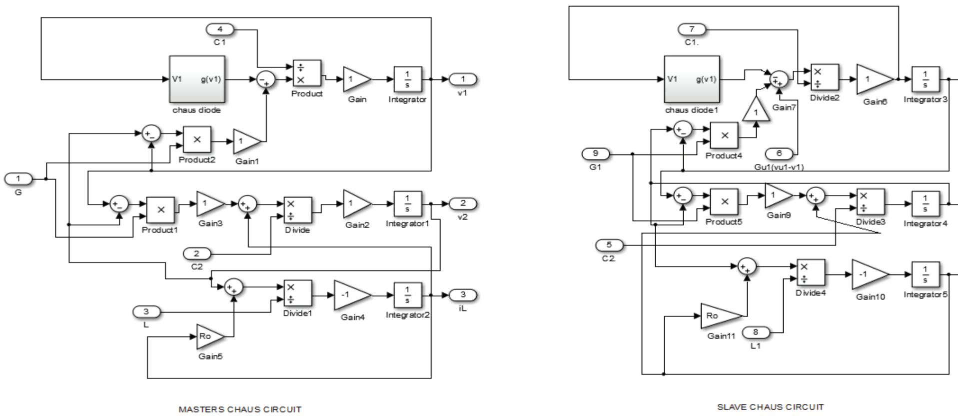

Figure 6. Model for master and slave Chua's oscillator.

Two Chua's oscillations with unidirectional coupling identical Chua's circuits.We design an adaptive controller to synchronize the two oscillators and tune the slave oscillator's parameter to the master oscillator's parameter. Using the ideal Chua's oscillator model is considered. In a master/slave configuration, the master Chua's and the slave Chua's oscillators are given by

Subtracting Slave Chua's oscillator and Master Chua's oscillator **(Figure 7)**

$$\frac{d\tilde{v}_1}{dt}-\frac{dv_1}{dt}=\frac{1}{C_1}\left(G\left(\tilde{v}_2-\tilde{v}_1\right)-g\left(\tilde{v}_1\right)+u_1\right)-\frac{1}{C_1}G\left(v_2-v_1\right)+g\left(v_1\right) \quad (18)$$

$$\frac{d\tilde{v}_2}{dt}-\frac{dv_2}{dt}=\frac{1}{C_2}(G\left(\tilde{v}_1-\tilde{v}_2\right)+\tilde{i}_L-\frac{1}{C_2}G\left(v_1-v_2\right)-i_L \quad (19)$$

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$$\frac{d\tilde{I}_L}{dt}-\frac{di_L}{dt}=\frac{1}{\tilde{L}}\left(-\tilde{v}_2-R_0\tilde{i}_L\right)-\frac{1}{L}\left(-v_2-R_0 i_L\right) \quad (20)$$

Where $u_1 \triangleq G_{u1}(v_{u1}-\tilde{v}_1)$.

Master/slave Chua's oscillator produces the error dynamics. We get

$$\dot{e}_{v1}=\frac{1}{C_1}\left(G\left(e_{v2}-e_{v1}\right)-c\left(\tilde{v}_1,v_1\right)e_{v1}+u_1\right)$$
$$\dot{e}_{v2}=\frac{1}{\tilde{C}_2}\left(G\left(\tilde{v}_1-\tilde{v}_2\right)+\tilde{i}_L\right)-\frac{1}{C_2}\left(G\left(v_1-v_2\right)+i_L\right) \quad (21)$$
$$\dot{e}_{iL}=\frac{1}{L}\left(-e_{v_2}-R_0 e_{iL}\right)$$

where $g(\tilde{v}_1)-g(v_1)=c(\tilde{v}_1,v_1)\,e_{v1}$, $e_{v1}\triangleq\tilde{v}_1-v_1$, $e_{iL}\triangleq\tilde{i}_L-i_L$ and $e_{v2}\triangleq\tilde{v}_2-v_2$

Consider the Master/Slave Chua's oscillator below.

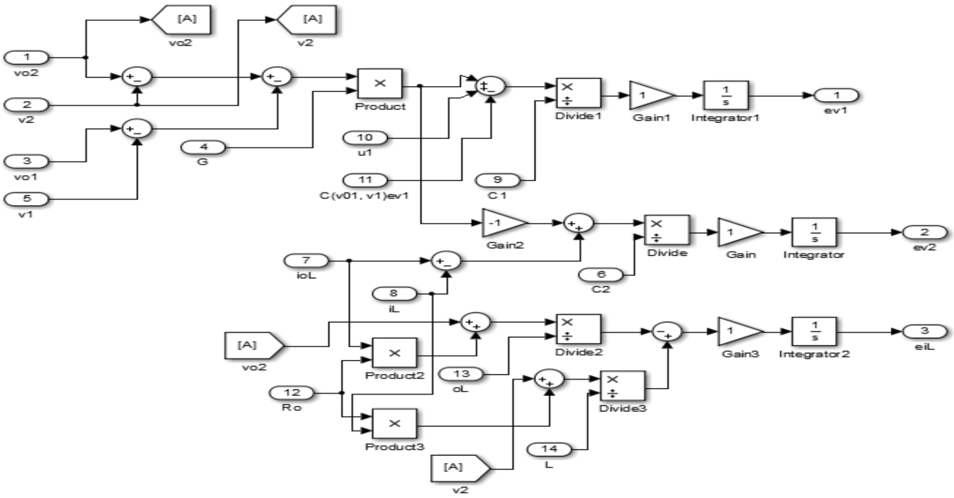

Figure 7. Model for master/slave Chua's oscillator.

CIRCUIT BOARD IMPLEMENTATION

The complete circuit schematics that are used in the physical implementation of master/slave Chua's oscillator synchronization. In order to case the implementation, a circuit board has been selected for realization of theChua's circuit shown in **Figure 8**. The circuit board of the master/slave system are connected to two analog oscilloscopes, and a regulated ±9V power supply.

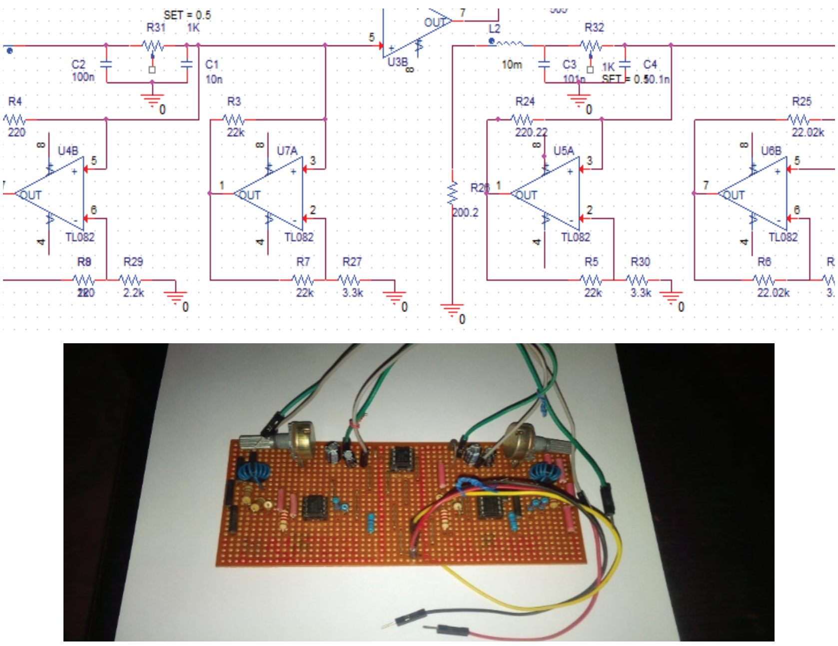

Figure 8. The Chua circuit implementation of the design.

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To test this setup for different parameter values of the master/slave system, we can simply vary the resistances (e.g., R_{im},i=1,2,3) on the circuit board. The values of the components used for the Chua circuit, excluding the Chua diode implementation are shown in **Table 2**.

Table 2. Value of components used in the Chua circuit implementation.

Master Chua's oscillator	Slave Chua's oscillator
R_1=22kΩ	$\tilde{R}_1$=22.2kΩ
R_2=22 kΩ	$\tilde{R}_2$=22.2 kΩ
R_3=3.3 kΩ	$\tilde{R}_3$=3.31 kΩ
R_4=220 Ω	$\tilde{R}_4$=220.2 kΩ
R_5=220 Ω	$\tilde{R}_5$=220.2 kΩ
R_6=2.2 kΩ	$\tilde{R}_6$=2.21 kΩ
R=1 k to 3.4 kΩ	$\tilde{R}$=1 k to 3.41 kΩ
C_1=10 nF	$\tilde{C}_1$=10.1 nF
C_2=100 nF	$\tilde{C}_2$=100.1 nF
op amp TL082	op amp TL082
L=10 mH to 18 mH	$\tilde{L}$=10 mH to 18 mH

SIMULATION RESULTS

MATLAB Simulink have been carried out to verify the feasibility of the designed procedure. In simulations, the CMOS realization of the CCII+ circuit shown in **Figure 9** has been performed with the COMS technology structure using, 0.5µm CMOS process parameters for nMOS and pMOS transistors. The Power supply voltages were +V_{DD}=-V_{SS}=1.5V, and biasing currents were I=50 µA. Therefore, the W (µm)/L (µm) ratios of MOS Transistors [24] for CCII+ and the dimensions of MOS transistors were used as specified in **Table 3**.

Table 3. Transistor dimensions of CMOS implemented CCII+.

NMOS transistor	Dimensions W (µm)/L (µm)	PMOS transistor	Dimensions W (µm)/L (µm)
M3, M4	100/0.5	M1, M2	100/0.5
M7, M8	3.33/0.5	M5, M6	3.33/0.5

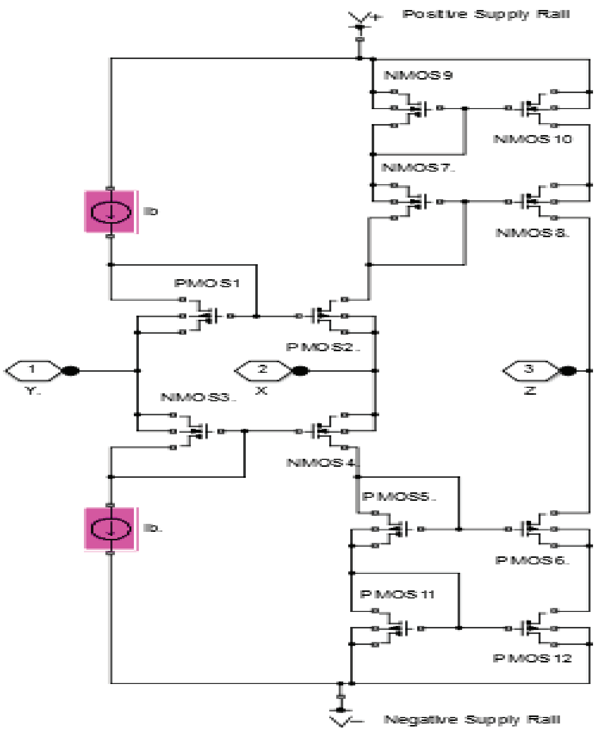

Figure 9. CMOS realization of the CCII+ used in simulations.

The dynamic behaviour is period-1 limited, the trajectory in phase space will orbit attractor of outer space for one cycle. In time domain, the voltage across the capacitor C_1 and C_2 will oscillate with one period, the voltage across the capacitor $C^{\sim}_1$ and $C^{\sim}_2$ will oscillate with one period When R is reduced further, the system will become period-2 limited, period-4 limited, period-8 limited, and finally the system becomes chaotic: attractor becomes strange attractor (Spiral-Chua attractor) the trajectory in phase space orbits the attractor with infinite period [25,26]. Since the non-linearity of Chua's diode is symmetric, two possible attractors exist in phase space, and the trajectory will orbit either one depends on the initial condition. When R is reduced even further, two attractors merge and become double scroll. In this case, the trajectory will orbit both at tractors. The two attractors in double scroll become closer to each other with lower R. Finally, when the R is so small that the operational amplifiers work in saturation region, the circuit is no longer chaotic but works in saturated region.

MATLAB-Simulink simulations are run to map the performance of the adaptive control laws derived as a function of the behaviour of the master Chua's oscillator which changes from chaotic to equilibrium behaviour. Each set of Simulations are run 1,000 times for 1,000 different values of C_1 ranging from 100 nF to 105nF. With each change in the C_1 value, the simulation result for the master Chua's attractor also changes. To illustrate the change in the master Chua's attractor with the change in the value of C_1, **Figure 3** provides the bifurcation diagram for the master Chua's oscillator for the 1,000 values of C_1. To capture the impact of component tolerances the slave Chua's oscillator parameters are increased by 0.1% (not including C_1).

The common setup for all simulations is as follows: simulations are run by using the Runge-Kutta 4^{th} order numerical solver with a fixed step-size of 10 microseconds for a simulation time of two seconds.

The initial conditions are selected to be $v_{10}= 9$, $v_{20} = 9$, $i_{L0}= 0$, $v^{\sim}_{10}=9$, $v^{\sim}_{20}=9$, and $i^{\sim}_{L0}=0$.

Since it takes time for the master/slave Chua's oscillator to evolve from the initial condition to reach the attractor corresponding to the chosen C_1 value. The parameters used in simulations are listed in **Table 3**.

Table 3. MATLAB simulation parameters.

Common parameters	MATLAB simulations (Master)	MATLAB simulations (slave)
	C_2=150 nF	$L^{\sim}_{(0)}$=10 mH
G_a=-0.40909 ms	L=18 mH	$C^{\sim}_{2(0)}$=150.5 nF
G_b=-0.75758 ms	C_1=150 nF	$C^{\sim}_1$=150.5 nF
E_1=1.1739 V	R_0=18 Ω	$R^{\sim}_0$=18.5 Ω
G_{u1}=1/500 S	G=1/100 S	$G^{\sim}$=1/100 S

Masters Chau's Oscillator

When R_1=18Ω, the circuit is period-1 limited, as shown in **Figure 10**. The transient waveform has one oscillation cycle, and the trajectory in phase space encircles the attractor for one time.

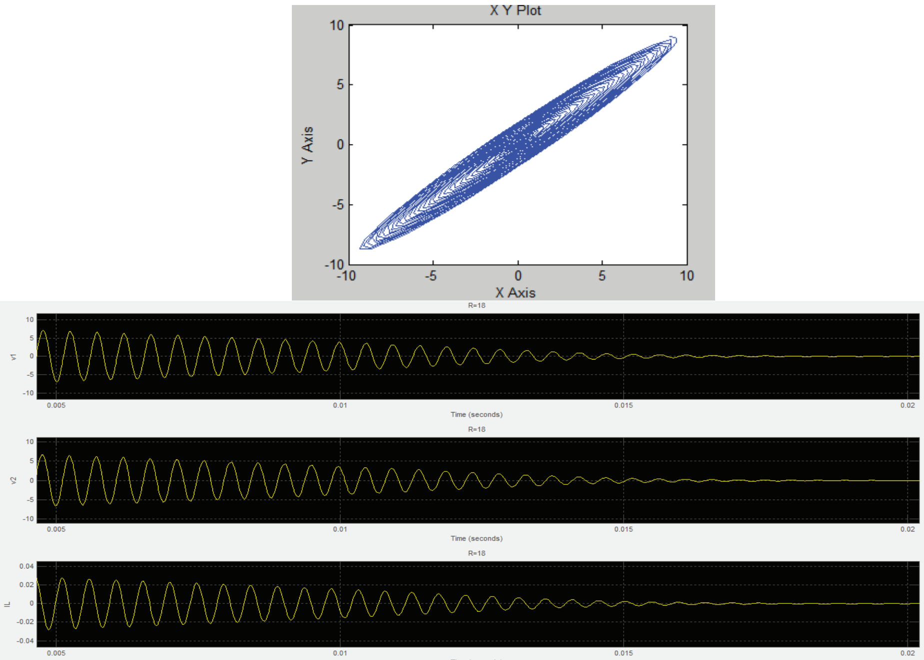

Figure 10. Transient waveform (a): phase trajectory; (b): when R1=18Ω.

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Slave Chau's Oscillator

When $R^{\sim}_{1}$=18Ω, the circuit is period-1 limited, as shown in **Figure 11**. The transient waveform has two oscillation cycles, and the trajectory in phase space encircles the attractor for one times.

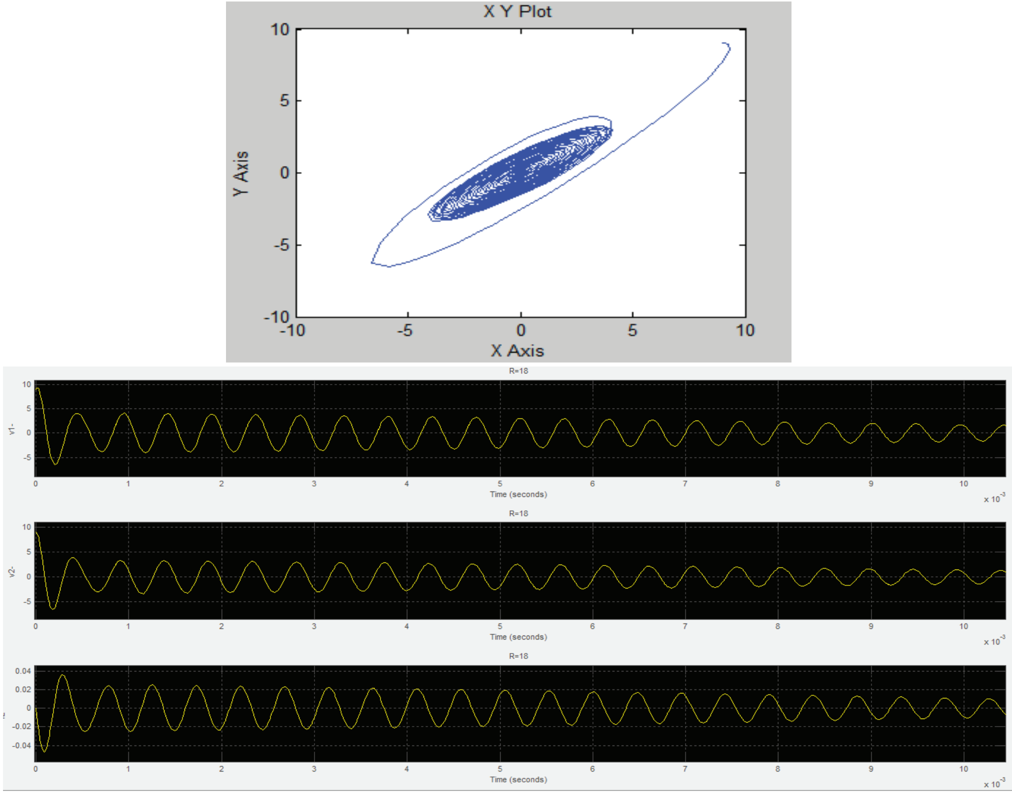

Figure 11. Transient waveform 2 (a): phase 2 space trajectory; (b): when R_1=20Ω.

Masters/Slave Chau's Oscillator

When R_o=1Ω, the circuit is period-1 limited, as shown in **Figure 12**. The transient waveform has two oscillation cycles, and the trajectory in phase space encircles the attractor for one times.

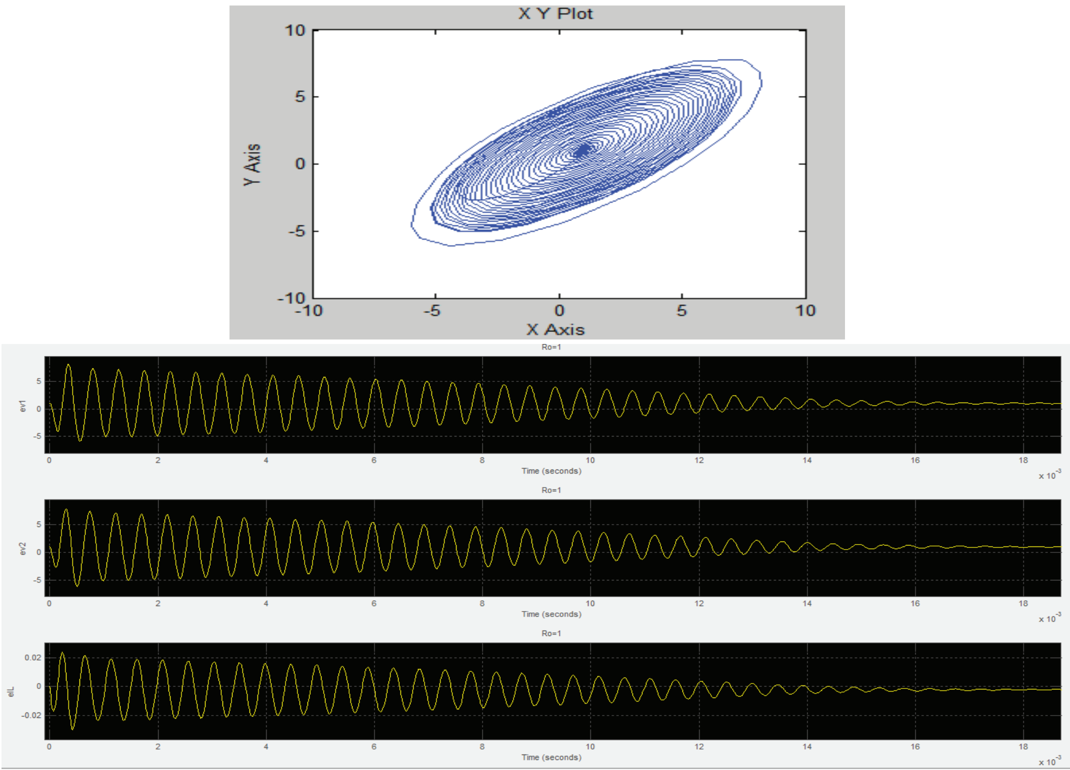

Figure 12. Transient waveform 3 (a): phase 3 space trajectory; (b): when R_0=1Ω.

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p-ISSN:2347-2316

Masters Chau's Oscillator

When R_2=20Ω, the circuit is period-2 limited, as shown in **Figure 13**. The transient waveform has two oscillation cycles, and the trajectory in phase space encircles the attractor for two times.

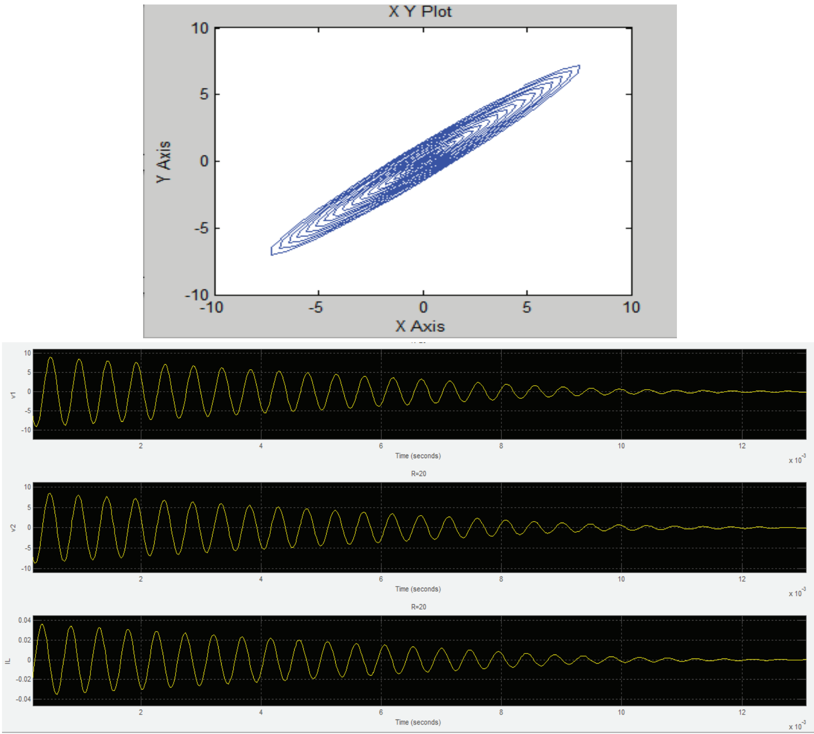

Figure 13. Transient waveform 4 (a): phase 4 space trajectory; (b): when R_2=20Ω.

Slave Chau's Oscillator

When $R^{\sim}_0$=20Ω, the circuit is period-2 limited, as shown in **Figure 14**. The transient waveform has two oscillation cycles, and the trajectory in phase space encircles the attractor for two times.

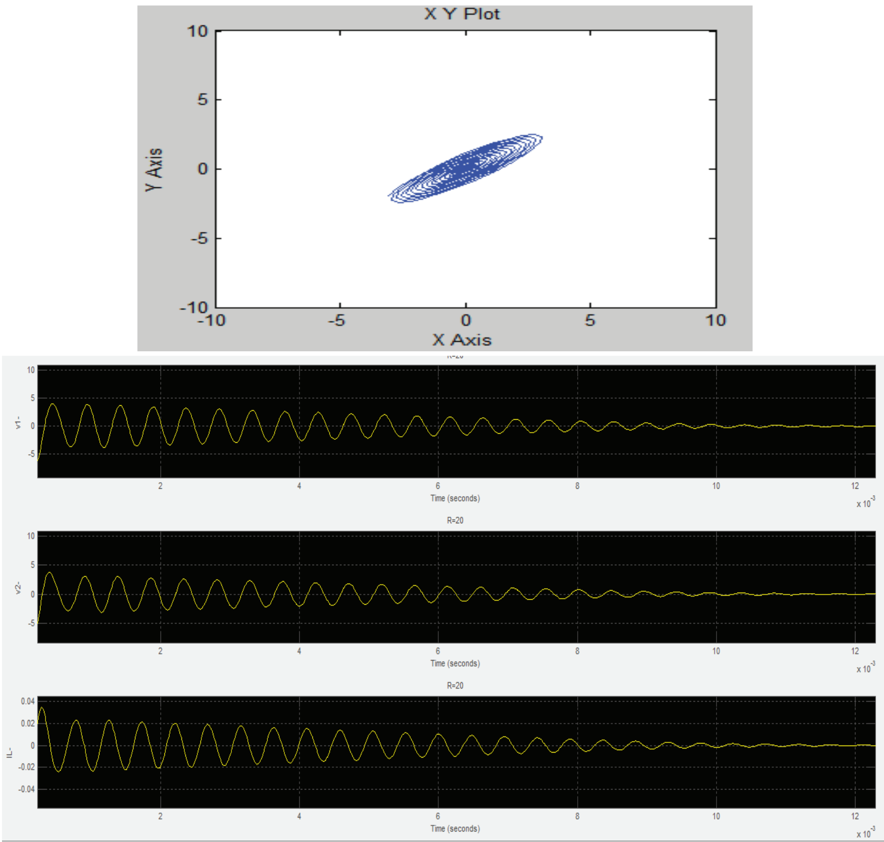

Figure 14. Transient waveform 5 (a): phase 5 space trajectory; (b): when $R^{\sim}_0$=20Ω.

Masters/Slave Chau's Oscillator

When R_0=1Ω, the circuit is period-2 limited, as shown in **Figure 15**. The transient waveform has two oscillation cycles, and the trajectory in phase space encircles the attractor for two times.

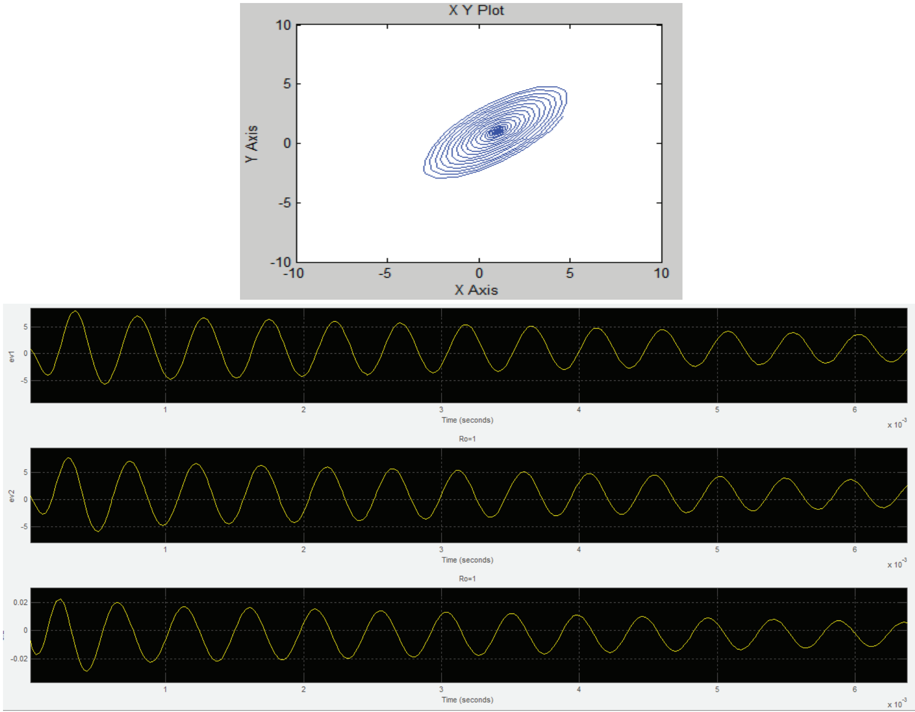

Figure 15. Transient waveform 6 (a): phase 6 space trajectory; (b): when R_0=1Ω.

CONCLUSION

In this paper a Synchronization of two Chua's circuit was designed using CCII+. CCII+ to realize a current conveyor based on two synchronized Chua's oscillator. Chua's diode is realized by using two Current Conveyors (CCII+) and 4 passive elements while the simulated inductance is realized by using four Current Conveyors (CCII+) and 3 passive elements. Parasitic effects of the implementation are analysed according to the general data provided by the manufacturer to explain the most susceptible points of the design despite assistance. The circuit is realized by differential (voltage to current) pairs feeding two capacitors, which carry the dynamics, with the key component being a (voltage to current) binary hysteresis circuit due to Linares. Hence, Master/Slave coupling between two Chua's oscillators for state v_1, v_2, v_1,and v_2 is easily achievable with just two resistors and one second current conveyors. Two Chau's circuits can be synchronized to have the same output waveform even with different initial conditions. The Chua's circuit may work in equilibrium region, period-n limit region, chaotic region or saturation region. In the synchronization of two Chua's circuit, the synchronization behaviour is more sensitive to R_0 mismatch than L,L~ and C,C~ mismatchs, as it decides the chaotic behaviour of the circuit. As a result, Synchronization of two Chua's circuit realized with only CCII+s has been proposed and verified experimentally. We analyse and demonstrated two of its practical applications in communication.

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