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IMPROVED REALIZATION OF MIXED-MODE CHAOTIC CIRCUIT

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An improved realization of mixed-mode chaotic circuit which has both autonomous and nonautonomous chaotic dynamics is proposed. Central to this study is inductorless realization of mixed-mode chaotic circuit using FTFN-based inductance simulator. FTFN-based topology used in this realization enables the simulation of ideal floating and grounded inductance. This modification provides an alternative solution to the integration problem of not only mixed-mode chaotic circuit but also other chaotic circuits in the literature using CMOS VLSI technologies. In addition to this major improvement, CFOA-based nonlinear resistor was used in the new realization of mixed-mode chaotic circuit. The usage of CFOA-based nonlinear resistor in the circuit's structure reduces the component count and provides buffered and isolated output.

Keywords: Chaos; mixed-mode chaotic circuit; FTFN-based inductance simulator; CFOA-based Chua's diode.

1. Introduction

Up to now, a variety of autonomous and nonautonomous chaotic circuits which can be effectively used in chaotic secure communication systems have been designed and described in the literature; see for example [Cuomo & Oppenheim, 1993; Special Issue, 1993, 1997; Itoh *et al.*, 1994; Itoh, 1999; Kolumban *et al.*, 1998; Parlitz *et al.*, 1992; Tamasevicius, 1997; Wu & Chua, 1993] and references therein. Chaotic circuits for use in chaotic secure communication systems must not only have a simple design but also a structure that is able to provide greater reliability in the form of a wide range of parameter variations and extra security keys. Mixed-mode chaotic circuit [Kılıç *et al.*, 2000] has such a chaotic circuit structure, that exhibits both autonomous and nonautonomous chaotic dynamics via switching method. This circuit's structure is extremely simple and it contains only one nonlinear resistor. In addition to the wide range of autonomous and nonautonomous chaotic circuit parameters, the switching method, which changes the chaotic dynamics of the circuit from autonomous to nonautonomous mode, can be used as an extra

security key in chaotic communication systems. Details of such an application of mixed-mode chaotic circuit to chaotic communications for transmission of analog signals can be found in [Kılıç & Alçı, 2001].

Inductorless realization of chaotic circuits greatly facilitates the experimental studies based on these circuits. This also enables the implementation of low cost, reliable, accurate and compact chaotic systems as integrated circuits. Such integrated circuits could be readily used in many chaos-based secure communication systems. Recently, several inductor-free realizations of chaotic circuits have been proposed [Cruz & Chua, 1993; Morgul, 1995; Torres & Aguirre, 2000]. These studies especially deals with the inductorless realization of autonomous Chua's circuit [Chua *et al.*, 1993]. Instead of inductor element, active inductance simulators have been used in these circuit structures and in general as an active element, Op-Amp and OTA-based building blocks are preferred.

On the other hand, the four terminal floating nullor (FTFN) has also been receiving considerable attention recently as it has been shown that an FTFN is very flexible and a versatile building block in active network synthesis [Higashimura, 1991]. This leads to growing attention in designing amplifiers, gyrators, inductance simulators, oscillators and filters which use FTFN as an active element [Çam *et al.*, 2000a; Çam *et al.*, 2000b].

In this work, the major improvement considered is the inductorless realization of mixed-mode chaotic circuit. For this purpose, instead of inductor elements in mixed-mode chaotic circuit, FTFN-based inductance simulators have been used. This FTFN-based topology enables to simulate ideal floating inductance and ideal grounded inductance in mixed-mode chaotic circuit. This improvement provides an alternative solution to integration problem of not only mixed-mode chaotic circuit but also other chaotic circuits in the literature using CMOS VLSI technologies.

In addition to inductor-free modification, current feedback Op Amp (CFOA)-based nonlinear resistor (Chua's diode) structure was used in the new realization of mixed-mode chaotic circuit. This CFOA-based Chua's diode has been reported in [Elwakil & Kennedy, 2000]. By using this realization of Chua's diode, component count is reduced and a buffered and isolated voltage output is available.

2. Circuit Description of Improved Mixed-Mode Chaotic Circuit

Original mixed-mode chaotic circuit is shown in Fig. 1. Mixed-mode chaotic circuit exhibits both autonomous and nonautonomous chaotic circuit dynamics. In the design of mixed-mode chaotic circuit, common dynamics of autonomous Chua's circuit [Chua *et al.*, 1993] and a nonautonomous MLC circuit [Murali *et al.*, 1994] were combined using a switching method [Kılıç *et al.*, 2000]. In this way depending on the states of the switches, mixed-mode chaotic circuit operates either in the chaotic regime determined by autonomous circuit part or in the chaotic regime determined by nonautonomous circuit part.

When the states of switches are S1-ON and S2-OFF, we have the standard nonutonomous chaotic circuit described in [Murali *et al.*, 1994] exhibiting a double-scroll chaotic attractor. In this case, the circuit is represented by the following set of two first-order nonautonomous differential equations:

$$C_1 \frac{dV_R}{dt} = i_{L1} - f(V_R) \tag{1}$$

$$L_1 \frac{di_{L1}}{dt} = -i_{L1}(R_1 + R_{S1}) - V_R + A\sin(wt) \tag{2}$$

where A is the amplitude and w is the angular frequency of the external periodic force V_{ac} in Fig. 1. The amplitude of the external forcing source can be used as the bifurcation parameter. By increasing the amplitude A from zero upwards, the circuit

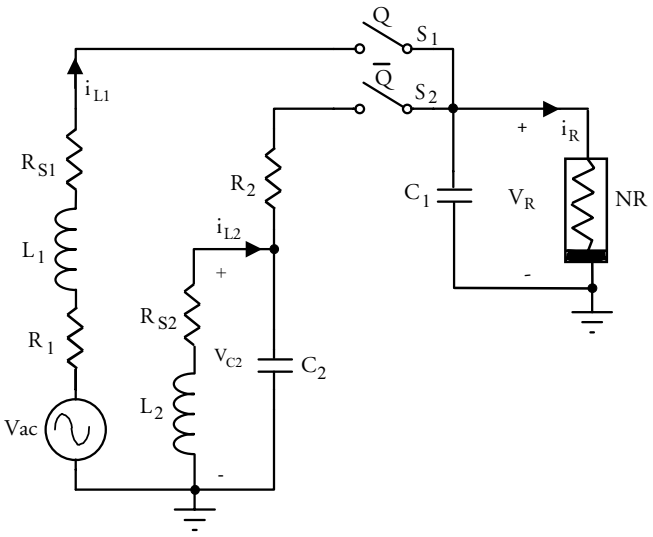


Fig. 1. Mixed-mode chaotic circuit.

exhibits the complex dynamics of bifurcation and chaos.

When the states of switches are S1-OFF and S2-ON, we have the standard autonomous Chua's circuit [Chua *et al.*, 1993] exhibiting a double-scroll Chua's chaotic attractor. In this case, the circuit is described in the following set of three first-order autonomous differential equations:

$$L_2\frac{di_{L2}}{dt} = -V_{C2} - i_{L2}\cdot R_{S_2} \tag{3}$$

$$C_2\frac{dV_{C2}}{dt} = i_{L2} - \frac{1}{R_2}(V_{C2} - V_R) \tag{4}$$

$$C_1\frac{dV_R}{dt} = \frac{1}{R_2}(V_{C2} - V_R) - f(V_R) \tag{5}$$

By reducing the variable resistor R_2 in Fig. 1 from 2000 Ω towards zero, the circuit exhibits the autonomous complex dynamics of bifurcation and chaos. In the original structure of mixed-mode chaotic circuit, the circuit realization in [Kennedy, 1992] was used for the nonlinear resistor and its i–v characteristic is defined as follows:

$$\begin{aligned} i_R &= f(V_R) \\ &= G_b V_R + 0.5\cdot(G_a - G_b) \\ &\quad \times (|V_R + B_p| - |V_R - B_p|) \end{aligned} \tag{6}$$

where the actual values of G_a, G_b and B_p are −0.76 mS, −0.41 mS and 1.0 V, respectively.

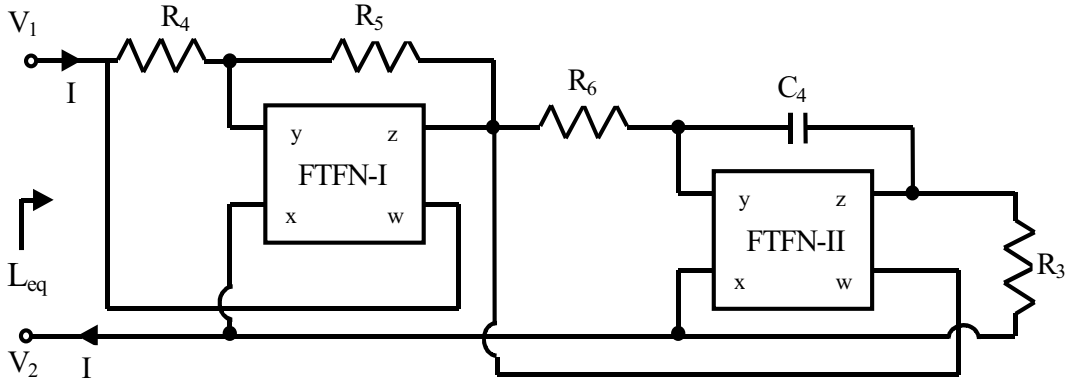


Fig. 2. FTFN-based inductance simulator.

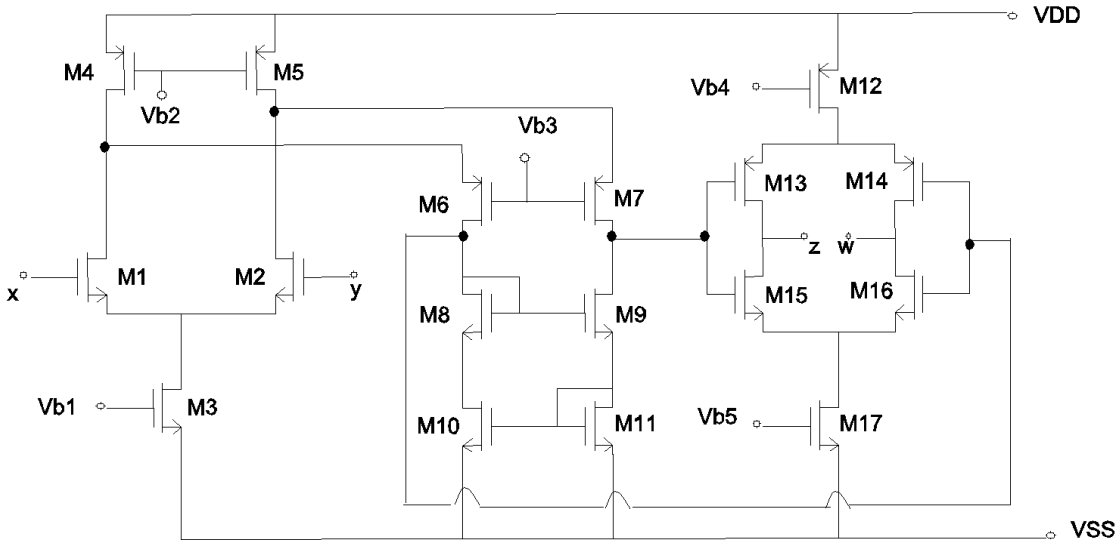


Fig. 3. A CMOS realization of the FTFN.

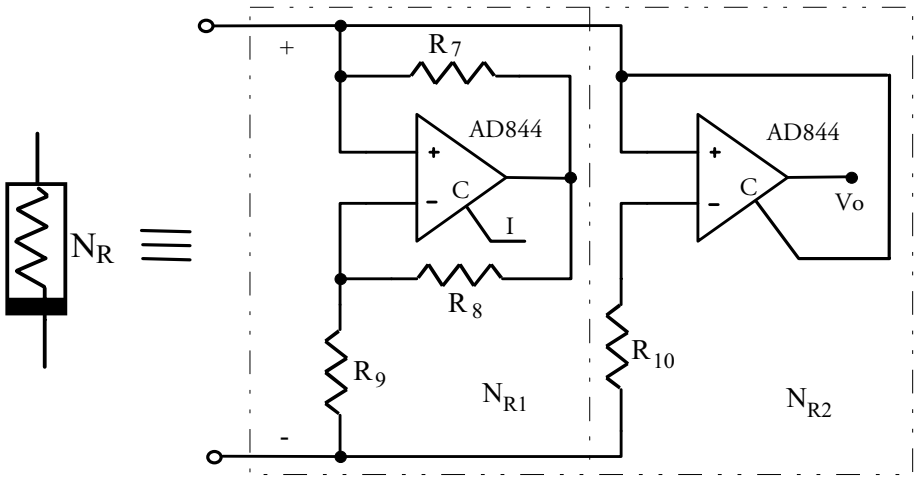


Fig. 4. CFOA-based Chua's diode.

In the new realization of mixed-mode chaotic circuit, as a major improvement, FTFN-based inductance simulators are used instead of flaoting inductance L_1 and grounded inductance L_2 in Fig. 1. FTFN-based floating inductance simulator is shown in Fig. 2. Routine analysis yields equivalent inductance between terminals 1 and 2 as:

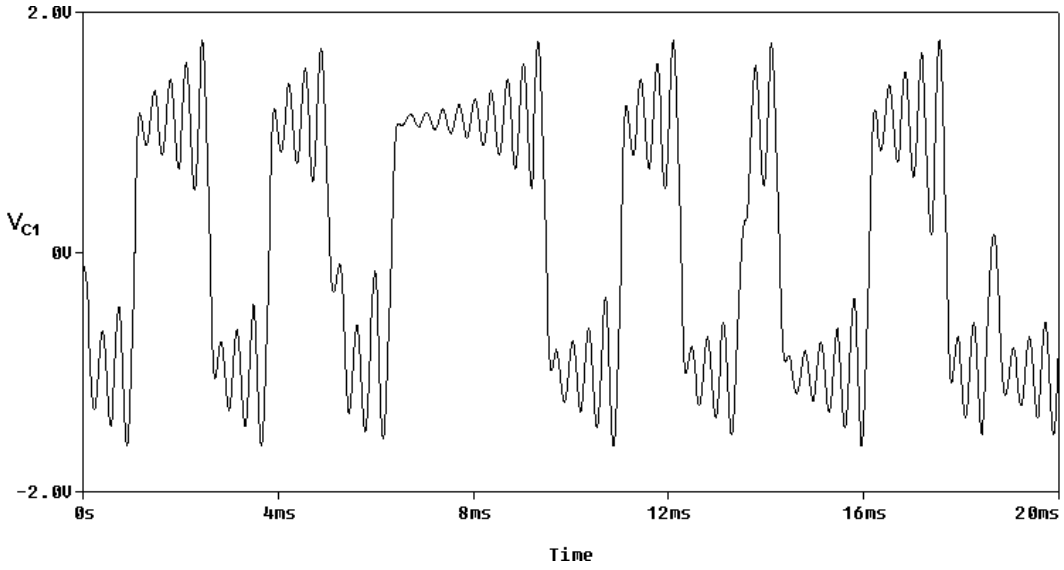
$$L_{\text{eq}} = \frac{C_4 R_3 R_4 R_6}{R_5} \tag{7}$$

In Fig. 2, the following element values are chosen: $R_3 = R_4 = R_5 = R_6 = 1$ KΩ, $C_4 = 18$ nF to simulate $L_1 = L_2 = 18$ mH. Floating inductance is also used as grounded inductor by connecting to ground one port of the floating inductance for simplicity. The PSpice simulations were performed using a CMOS realization of FTFN, shown in Fig. 3, in literature with same parameters [Çam & Kuntman, 2000].

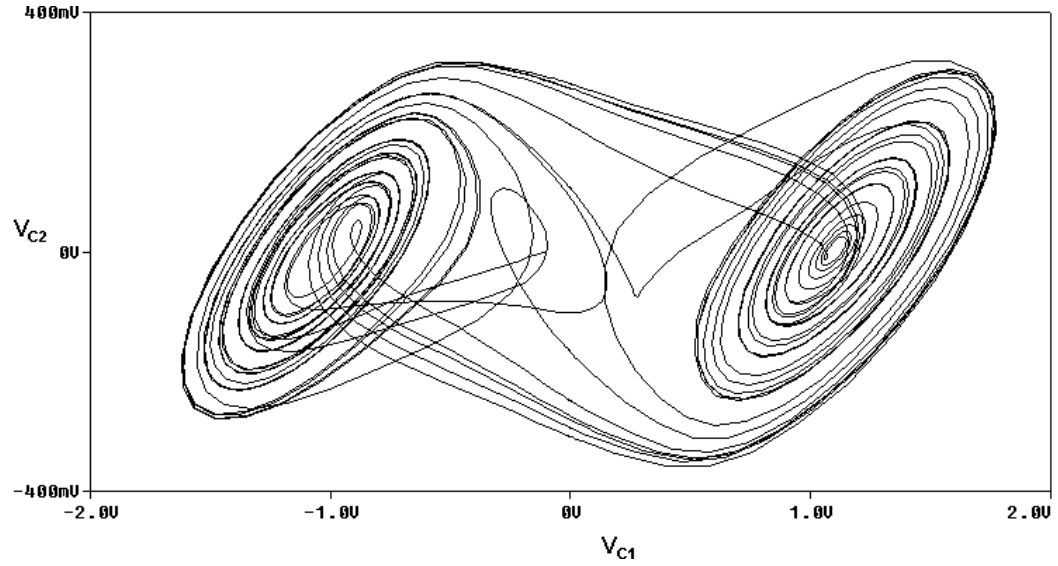
As a second improvement, we used the CFOA-based circuit structure for the nonlinear resistor reported in [Elwakil & Kennedy, 2000]. CFOA-based circuit realization of the nonlinear resistor combines attractive features of the current feedback op amp operating in both voltage and current modes. This CFOA-based nonlinear resistor's circuit structure is shown in Fig. 4. As shown in the figure, Chua's diode is implemented with parallel connection of a voltage-mode CFOA which operates as a nonlinear voltage-controlled negative impedance converter (VNIC) associated with resistors R_7, R_8 and R_9, and a current-mode CFOA which operates as a linear NIC by connecting as a CCII with resistor R_{10}. With this configuration, in addition to reduced component count, the buffered output V_o is available and this output is isolated from other circuit components. In PSpice simulation experiments, we used AD844 macro-model of Analog Devices for CFOA with ±9 V biasing and we settled the other circuit parameters of nonlinear resistor as $R_7 = R_8 = 22$ kΩ, $R_9 = 500$ Ω and $R_{10} = 2.2$ kΩ. In addition to these components, a load resistor $R_L = 5$ kΩ is used in the current output of the first CFOA. The details of CFOA-based Chua's diode can be found in [Elwakil & Kennedy, 2000].

3. Simulation Results

For the PSpice simulations, in addition to the above arrangement of FTFN-based inductance simulator for ideal floating inductance L_1 (18 mH) and ideal grounded inductance L_2 (18 mH) and, CFOA-based nonlinear resistor in mixed-mode chaotic circuit, we fixed the other circuit parameters in Fig. 1 as $C_1 = 10$ nF, $C_2 = 100$ nF, $R_1 = 1340$ Ω, $R_2 = 1700$ Ω, $R_{S1} = 12.5$ Ω, $R_{S2} = 12.5$ Ω, $A = 0.1$ V and the frequency of the external forcing source is 8890 Hz for which the circuit exhibit double-scroll chaotic behavior. While improved mixed-mode chaotic circuit's autonomous (S1-OFF, S2-ON) chaotic waveform and double-scroll attractor are illustrated in Fig. 5, improved mixed-mode chaotic circuit's nonautonomous (S1-ON, S2-OFF) chaotic waveform and double-scroll attractor are illustrated in Fig. 6.



(a)



(b)

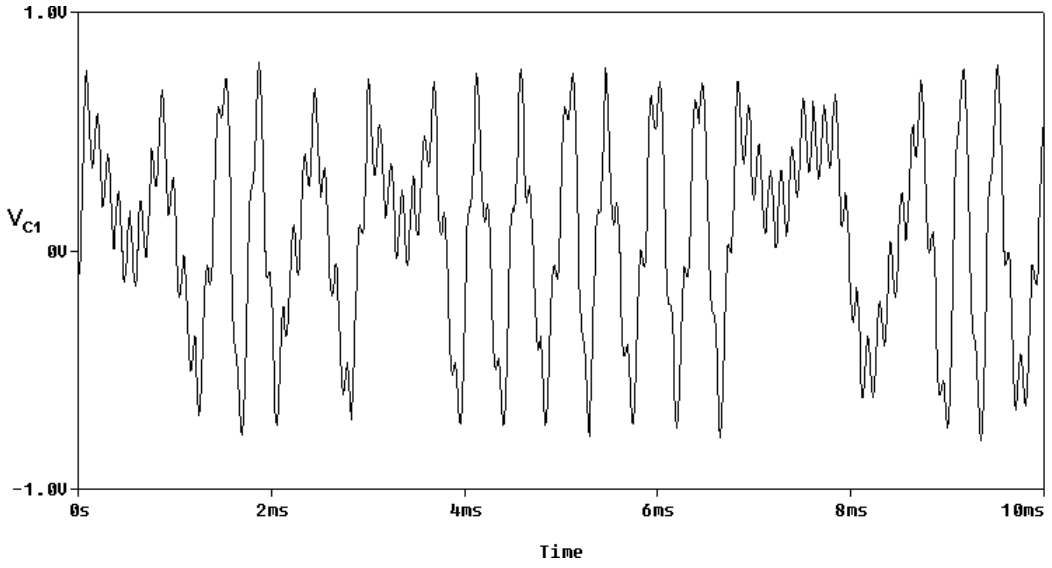
Fig. 5. When improved mixed-mode chaotic circuit oscillates in autonomous mode (S1-OFF, S2-ON), (a) the chaotic waveform of the voltage across capacitor C_1 in Fig. 1, and (b) double-scroll chaotic attractor.

4. Conclusion

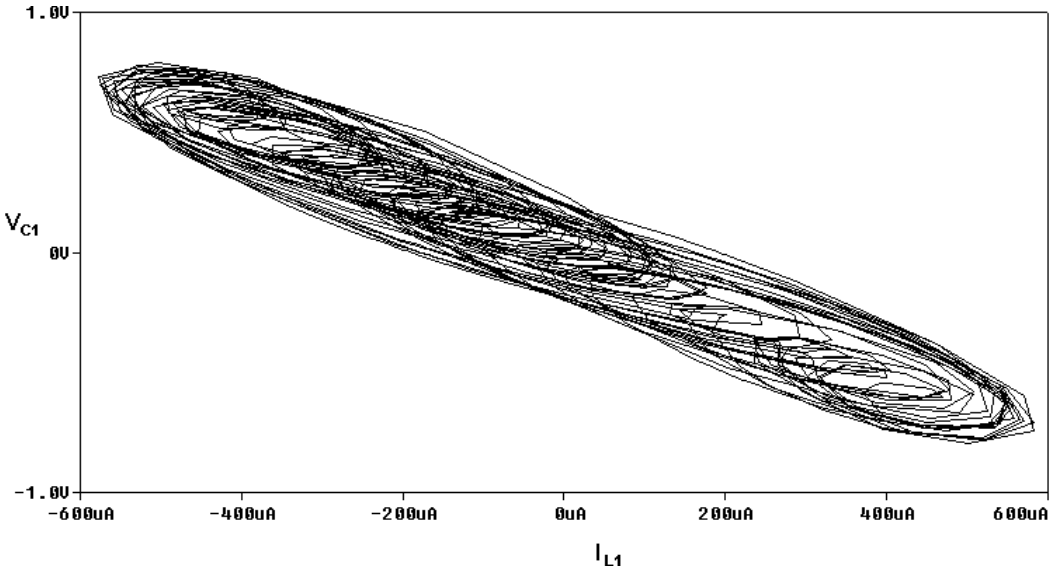
The improved realization of mixed-mode chaotic circuit using FTFN-based inductance simulator and CFOA-based nonlinear resistor has been introduced. The simulation results indicate that improved mixed-mode chaotic circuit using FTFN and CFOA topology exhibit its original chaotic behaviors. The CMOS implementation of mixed-mode chaotic circuit using FTFN-based inductance simulators provides new possibilities to the design of the integrated circuit realization of chaotic communication systems. In addition, using CFOA for nonlinear resistor in mixed-mode chaotic circuit reduces the component count and provides a current output and buffered voltage output.

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(a)



(b)

Fig. 6. When improved mixed-mode chaotic circuit oscillates in nonautonomous mode (S1-ON, S2-OFF), (a) the chaotic waveform of the voltage across capacitor C_1 in Fig. 1, and (b) double-scroll chaotic attractor.

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