A simple CMOS chaotic integrated circuit

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Abstract: A chaotic integrated circuit is designed and fabricated using a 0.35 μm CMOS process. The circuit iterates an N-shaped transfer function using a small analog neural network. One of the advantages of the proposed circuit is its small circuit area with only 13 MOS transistors. The circuit generates both an analog and a digital signal that can be used to create true random bit sequences.

Keywords: Chaotic Circuits, Neural Networks, CMOS

Classification: Integrated circuits

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1 Introduction

Chaos refers to the impossibility of making accurate long-term predictions about the behavior of non-linear systems. During last decades there has been a high interest in the design and analysis of chaotic systems given their parallelism with nature behavior. In particular, the design and implementation of chaotic circuits has found different fields of application that include secure communications [1], robot control [2], or noise sources implementation [3] frequently employed in speech processing applications or to test the dynamic behavior of electronic systems. Chaotic circuits are also used as random number generators for applications in the security domain of networks and wireless communications [4] and for both analog and digital testing [5]. In particular, neural networks exhibiting a chaotic behavior has been applied to optimization problems [6].

Many chaotic oscillator designs were introduced during last two decades. One of the most known chaotic circuits is the Chua’s circuit [7, 8] containing four linear elements (two capacitors, one resistor and one inductor) and a nonlinear resistor called Chua’s diode constructed using operational amplifiers. An integrated implementation of Chua’s circuit was presented in [9] using a $2\mu\text{m}$ CMOS technology, and occupying a silicon area of $2.5 \times 2.8\text{mm}^2$. Other researchers [10, 11, 12] present different chaotic oscillators using inductances, resistors and nonlinear elements (similarly to Chua’s circuit) requiring the use of several operational amplifiers, with a considerable impact on the circuit area.

To overcome those area problems a simpler design has been recently introduced using a total of 20 MOS transistors [13]. The circuit implements the double-scroll chaotic equation and its effectiveness has been demonstrated using SPICE simulations. More recently a transistor-based chaotic circuit has been proposed [14]. The circuit uses a bipolar transistor, two capacitors and two resistors, but requires the use of an external sinusoidal oscillator for its proper operation.

In this work we present an autonomous low-cost chaotic Integrated Circuit (IC). A low area of integration is achieved due to the use of a relatively low number of transistors. The chaotic behavior is reproduced implementing a N-shaped iteration map using three coupled neurons designed with a simple CMOS scheme (see [15] for a detailed description of how the N-shaped iteration map may reproduce a chaotic behavior). The circuit was implemented on a $0.35\ \mu\text{m}$ technology and integrated in $47\ \mu\text{m} \times 57\ \mu\text{m}$ of silicon area. It generates a digital output that can be used to create a true random bit sequence. The proposed circuit is, to the best of our knowledge, the smallest chaotic integrated circuit that has been built. The rest of this paper is organized as follows: in section 2 we show the basic principles of the proposed chaotic system, in section 3 we show the experimental results and finally, in section 4 we present the conclusions.

2 Chaotic neural network design

The proposed design obtains the chaotic signal from a small neural network. Neurons are non-linear elements that implement a sigmoid-like function ($f(x)$) to the result of adding and weighting all the neuron inputs I_i .

Fig. 1. Circuit implementation of the chaotic neural network. Two outputs, an analog and a digital signal (V_{oa} and V_{od}) are generated.

Fig. 2. (a) Dynamic characteristics for the circuit when $V_{c1} = 0V$ and $V_{c2} = 0.68V$. An analog (bottom signal) and a digital output (middle signal) are obtained. The threshold level of inverters connected to V_{oa} is shown as a dashed line with V_{oa} . (b) Circuit scheme for random bit generation.

The neuron response (y) is therefore expressed as follows:

$$y = f \left(\sum_i \omega_i I_i \right) \quad (1)$$

To reproduce a chaotic behavior, we designed a small network with three neurons to implement a N-shaped transfer function $N(x)$ as it has been reported that, under specific conditions, iterations on a N-shaped map may reproduce a chaotic behavior (see [15]). The state of the system x_n is updated at each iteration through the N-shaped transfer function $N(x_n)$ so that:

$$x_{n+1} = N(x_n) \quad (2)$$

The function $N(x)$ may be reproduced with three coupled neurons, each one implemented using MOS transistors (see Fig. 1). Each neuron circuit is reproducing Eq. (1) with pre-defined values for the input weights (ω_i) that depend on transistor sizing (see Fig. 1 to see the specific transfer function of each neuron). We also included two controlling voltages (V_{c1} and V_{c2}) to change the PMOS resistance of two neurons of the circuit, thus modifying the transfer function of the whole system. A transfer function similar to a sigmoid is obtained at the output of each neuron due to the non-linear characteristics of MOS devices. The channel width of NMOS transistors has been selected to obtain the proper weight for the inputs. The transfer curve obtained by the whole neural network depends on the selected values for V_{c1}

and V_{c2} . For specific values of these controlling voltages we can obtain an N-shaped transfer function that allows the reproduction of the chaotic behavior. A measurement of the N-shaped transfer function of the fabricated circuit is shown in Fig. 1 ($V_{oa}(V_{in})$).

The circuit is designed to provide two signals, one analog and the other digital (V_{oa} and V_{od}). Two transmission gates controlled by an external clock are serially connected to the neural network. When the clock signal is low, the voltage V_{oa} is evaluated by the network while when the clock is high the iteration $N(V_{oa})$ replaces the previous V_{oa} value. The final result is the iteration of Eq. (2) at each clock cycle. Finally V_{od} is generated from V_{oa} using CMOS inverters.

The proposed circuit was fabricated using a $0.35\ \mu\text{m}$ standard CMOS process. The nominal supply voltage is 3.3V while the total circuit dimensions are $47\ \mu\text{m} \times 57\ \mu\text{m}$. A photograph of the fabricated prototype is included as an inset in Fig. 1.

3 Experimental results

In Fig. 1 we show the measured transfer function of the system when the controlling voltages are settled to specific voltage values. We also provide the identity function ($y(x) = x$) since the output signal is chaotic only when the intersection between such a function and $N(x)$ occurs when $N(x)$ is decreasing [15]. Parameters V_{c1} and V_{c2} were fixed to 0V and 0.74V respectively.

In Fig. 2 (a) we show the dynamic behavior of the circuit when the clock signal oscillates at 0.18MHz . Two non-periodic signals (V_{od} and V_{oa}) are obtained. From the digital signal (V_{od}) we can generate a true random signal. In Fig. 2 (b) we show a circuit configuration that can be used to obtain a true random sequence that pass the FIPS-140-2 test suite (standardized test to accredit the quality of random bit sequences). A 8-bit shift register is serially filled with the product of performing the XOR function of V_{od} and the output bit of the register. In contrast to pseudo-random signal generators as LFSR counters, the bit sequence generated does not present a periodic behavior (an LFSR of n -bits presents a period of repetition of $2^n - 1$ bits). True random bit streams are ideal to implement stochastic-based computations [16, 17] in which true random sequences are needed to generate high quality stochastic signals [17].

In Fig. 3 (a) we show that the fabricated circuit present the phenomena of period doubling bifurcation cascade. The bifurcation diagram is obtained varying the controlling voltage V_{c1} between 0 and 1.6V . Fig. 3 (a) has been obtained by plotting the V_{oa} signal vs. V_{c1} at each iteration of Eq. (2) ($V_{oa}(V_{c1})$). Each division of the oscilloscope is equivalent to 200mV . We computed the Lyapunov exponents of the dynamic system when varying the controlling voltage V_{c2} . Lyapunov exponents constitute a useful metric for the estimation of the system sensitivity to initial conditions. The level of chaos is directly related to the Lyapunov exponent values since positive (negative) exponents are related to chaotic (periodic) behavior. Two trajectories with

Fig. 3. (a) Bifurcation diagram obtained when varying V_{c1} (plot of V_{oa} vs. V_{c1}) (b) Lyapunov exponent value as a function of the controlling voltage V_{c2} .

nearby initial conditions diverge, on average, at an exponential rate characterized by the Lyapunov exponent. Therefore, the separation between two trajectories (δx) presents a time evolution given by:

$$|\delta x_k| = |\delta x_0| e^{\lambda k} \quad (3)$$

where δx_k is the separation between the two trajectories in the k -th iteration, and δx_0 is the initial separation. We computed the Lyapunov exponents using the technique described in [18] for different values of V_{c2} (see Fig. 3 (b)) when V_{c1} is fixed to 0V. It is shown that λ is positive (and therefore the behavior is chaotic) when $V_{c2} < 0.9V$.

4 Conclusion

A simple fully-CMOS neural network circuit exhibiting a chaotic behavior has been presented and validated experimentally on a $0.35\mu m$ technology. The circuit presents a small area of integration and is implemented using MOS transistors only. The chaotic nature of the circuit is demonstrated experimentally through the computation of the Lyapunov exponents and the bifurcation diagram. To the best of our knowledge this is the smallest chaotic integrated circuit that has been built. The circuit is able to reproduce a

true random bit sequence that can be used to implement stochastic-based computations [17].

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