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Programmable multi-direction fully integrated chaotic oscillator

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ABSTRACT

This paper presents a digitally programmable multi-direction fully integrated chaotic oscillator. Unlike the conventional chaotic oscillators, the proposed digitally programmable multi-direction chaotic oscillator is fully integrated in one single chip, and it achieves lower supply voltage, lower power dissipation and smaller chip area. Moreover, by controlling the digitally programmable MOS switches turning on and off, the presented chaotic oscillator can provide chaotic oscillation in three different directions. The proposed digitally programmable multi-direction fully integrated chaos oscillator is verified with Cadence IC Design Tools. The post-layout simulation results demonstrate that the chaotic oscillator consumes 99.5 mW from ±2.5 V supply voltage, and it takes a compact chip area of 0.177 mm^2. The integrated chaos oscillator has a wide range of practical application prospects in chaotic communications or other applications demanding portable chaos systems.

1. Introduction

Chaos could be widely used in various chaos-based engineering applications such as secure communications [1–4], chaotic signal radar [5], chaos-based analog-to-information conversion [6], etc. More and more novel chaos systems with complex dynamic characteristics are proposed, and these chaos systems are further verified by using off-the-shelf electronic components in recent years [7–19].

The ultimate development direction of chaos circuits must be the appearance of their integrated circuits, just like the development paths of the fully integrated operational amplifiers, power amplifiers, RF transceivers, etc. The realizations of chaos systems using off-the-shelf electronic components with bread boards are basic validations, and they prove the observability and achievability of chaotic systems. Usually, the bread board-based circuits are not portable and unstable, and they have higher supply voltage and larger power consumption than their fully integrated counterparts. Obviously, the existing chaos circuits using off-the-shelf electronic components with bread boards are far from practical applications. Fully integrated chaos system on a single chip is the direction of development of chaos circuits, which will greatly enhance the practicality of chaos circuits.

Based on the existing chaos circuits and systems, a new digitally programmable multi-direction fully integrated chaos oscillator is presented and verified in this paper. The Cadence IC Design Tools post-layout simulation results verify that the presented digitally programmable multi-direction fully integrated chaos oscillator is feasible and achievable, and the fully integrated method of chaos oscillators will further promote the practical applications of chaotic circuits and systems.

2. Digitally programmable multi-direction chaotic systems

2.1. The jerk chaotic system

The classic jerk system is given as [20–24]:

$$\begin{cases} \dot{x} = y \\ \dot{y} = z \\ \dot{z} = a[-x - y - z + f(x)] \end{cases} \tag{1}$$

where *x*, *y* and *z* are state variables, *a* is a positive real number, and *f(x)* is a staircase nonlinear function. The staircase nonlinear function *f(x)* can be expressed as:

$$f(x) = A\left[-\operatorname{sgn}(x) + \sum_{i=0}^{(N-2)/2} (\operatorname{sgn}(x + (2i+1)A) + \operatorname{sgn}(x - (2i+1)A))\right],$$
$$N = even \geq 2 \tag{2}$$

or

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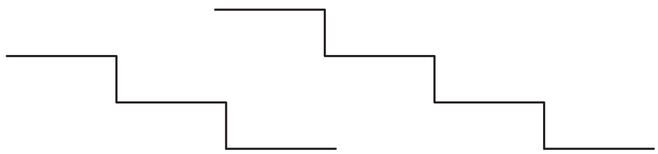

Fig. 1. The staircase function: $N=2$ (left), N = 3 (right).

$$f(x)=A\left[\sum_{i=0}^{(N-3)/2}(\operatorname{sgn}(x+(2i+1)A)+\operatorname{sgn}(x-(2i+1)A))\right], \quad N=odd\geq 3 \tag{3}$$

where A is a positive real number, N and i are positive integers, and sgn(x) is the symbolic function.

The staircase functions expressed in equations (2) and (3) are presented in Fig. 1. If the non-linear staircase function *f(x)* ($N=2$ left) is added in x axis, there will be two scrolls in x direction, and two scrolls will be observed in x-y and x-z planes; If the non-linear functions *f(x) and f(y)* ($N=2$ left) are added in x and y axis, there will be two scrolls in x and y directions respectively, and two scrolls will be observed in *x-z* and *y-z* planes, four scrolls in *x-y* plane; If the non-linear functions *f(x)*, *f(y)* and *f(z)* ($N=2$ left) are added in *x*, *y* and *z* axis, there will be two scrolls in *x*, *y* and *z* directions respectively, and four scrolls will be observed in *x-y*, *x-z* and *y-z* planes.

Based on the classic jerk system, it is easy to get its two-direction state function:

$$\begin{cases}\dot{x}=y-f(y)\\ \dot{y}=z\\ \dot{z}=a[-x-y-z+f(x)+f(y)]\end{cases} \tag{4}$$

where *x*, *y* and *z* are state variables, *a* is a positive real number, *f(x)* and *f(y)* are identical staircase nonlinear functions. The expression of *f(x)* is also described in equations (2) and (3), and the realization of *f(y)* is replacing *x* in equations (2) and (3).

The three-direction state function of the jerk system is

$$\begin{cases}\dot{x}=y-f(y)\\ \dot{y}=z-f(z)\\ \dot{z}=a[-x-y-z+f(x)+f(y)+f(z)]\end{cases} \tag{5}$$

where *x*, *y* and *z* are state variables, *a* is a positive real number, *f(x)*, *f(y) and f(z)* are identical staircase nonlinear functions. The expression of *f(x)* is also described in equations (2) and (3), and the realization of *f(y)* and *f(z)* are replacing *x* in equations (2) and (3), respectively.

2.2. The digitally programmable multi-direction chaotic system

According to the one-direction, two direction and three-direction jerk chaotic systems, the new digitally programmable multi-direction jerk chaotic system is depicted in equation (6).

$$\begin{cases}\dot{x}=y-f(y)\\ \dot{y}=z-f(z)\\ \dot{z}=a[-x-y-z+f(x)+f(y)+f(z)]\end{cases} \tag{6}$$

Controlled by S_1 and S_2

Controlled by S_3 and S_4

The proposed digitally programmable multi-direction jerk chaotic system has the same expression with equation (5). However, by controlling the switches in the signal paths of the staircase nonlinear functions *f(y)* and *f(z)*, the proposed digitally programmable multi-direction jerk chaotic system can realize one-direction, two direction and three-direction chaotic oscillations. There are four switches (S_1, S_2, S_3 and S_4) in the chaotic system, adding or removing the staircase nonlinear function *f(y)* is controlled by S_1 and S_2, and adding or removing the staircase nonlinear function *f(z)* is controlled by S_3 and S_4.

When the switches S_1, S_2, S_3 and S_4 are all turned off, equation (6) is a classic one-direction chaotic system; when the switches S_1 and S_2 are turned on, S_3 and S_4 are turned off, equation (6) is a two-direction chaotic system; when the switches S_1, S_2, S_3 and S_4 are all turned on, equation (6) is a three-direction chaotic system.

3. Circuit implementation

In order to realize the fully integrated digitally programmable multi-direction jerk chaotic system in equation (6), there are two key problems to be solved:

(1) A low voltage low power operational amplifier with simple structure suitable for integration should be designed.
(2) The typical parameters of jerk circuit are not suitable and reasonable for integration, especially the capacitors. According to the standard GlobalFoundries' 0.18 µm CMOS RF process, the maximum allowable value of a capacitor is less than 40 pF. The typical values of the capacitors in the jerk circuits are 1–100 nF, and it is not possible to realize 1–100 nF capacitors in integrated circuits.

3.1. Implementation of operational amplifier

In a fully integrated chaotic system, complex and high performance operational amplifier is not necessary, and the designed low voltage low power two-stage operational amplifier with simple structure for the fully integrated digitally programmable multi-direction chaotic system is presented in Fig. 2. The supply voltage of the designed operation amplifier is $V_{CC}=-V_{SS}=2.5$ V. The P-channel transistors M_7-M_9 [25] and N-channel transistors M_{10}-M_{11} consist of a double-ended input single-ended output differential input stage; M_{12} and M_{13} consist of the second common source amplifier stage; M_{14} and capacitor *C* consist of the frequency compensation network between the two stages; the transistors M_1-M_6 consist of the bias circuit of the operational amplifier.

The simulated amplitude and phase frequency characteristics of the operation amplifier are presented in Fig. 3. From the marks M_0-M_3, it is clear that the voltage gain of the operation amplifier is about 30 dB, its 3 dB bandwidth is 218.5 KHz, and the phase margin is about 86.22°. Its static power consumption is about 5.85 mW with ±2.5 V supply voltage.

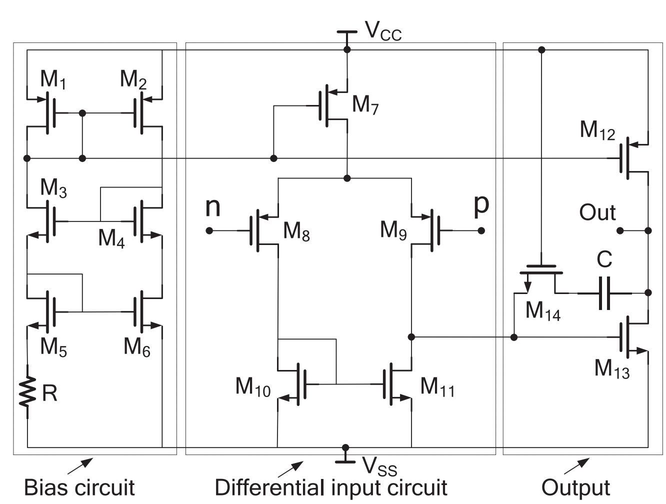

Fig. 2. The designed operation amplifier.