

Design and Implementation of a Wideband Practical Chua's Chaotic Signal Generator

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Abstract. A chaotic signal based on current conveyor is proposed in light of the deficiency in the wideband non-integrated Chua's chaotic signal generator currently in use. In order to further broaden the operating frequency, Chua's graded resistance is realized and its conductance is increased through the current conveyer. This paper also validates the existing linear interval bandwidth of active inductors. A practical broadband chaotic signal generator is proposed, introducing a synchronization function that can be applied in the field of communication. The circuit has been designed, simulated, realized in hardware and tested. The experimental results are in good agreement with simulation results, which confirms the validity of the design.

Keywords: Chua's circuit, current conveyer, secure communication

1. Introduction

This paper has studied and analyzed the existing wideband chaotic circuit before propose a new kind of chaos signal generator. The existing solutions for wideband chaotic circuits are mainly divided into two categories: one is digital implementation based on FPGA and the other is implemented based on CMOS integrated circuit [1-3].

Chaotic signal has a wide range of applications in secure communication. Whether it is asynchronous communication, using chaotic signal as a pseudo-random sequence generator, or setting the initial condition of chaotic signal as a cipher, the first problem to be solved is the realization of signal source. The bandwidth and stability of a signal source play an important role in its application. Chua's circuit is the simplest chaotic circuit, which produces chaos by introducing Chua's diode. Scholars at home and abroad have conducted in-depth research on Chua's circuit [4,5]. However, the current Chua's circuit still has the problem of limited bandwidth. The overall bandwidth of Chua's circuit based on voltage feedback is between 100-10KHz, which cannot meet the encryption requirements except for audio signals. There are many limitations in the circuit using voltage feedback operational amplifier as components of an active Chua diode. The most fundamental limitation is the contradiction between its bandwidth and gain. The GBW is a fixed value, which limits the operating frequency of this circuit.

Current feedback operational amplifier (CFB) is a new type of operational amplifier based on current feedback. Its input is no longer a differential pair but a buffer with a gain of 1. The slow rate of such current feedback operational amplifier is extremely high. Take AD844 as an example, its slew rate can reach 2000 V/ μ s. In addition, AD844 also has a TZ node, which is always proportional to the input error current, and the slew rate limitations associated with the large signal response of the op amps do not occur. In practice, the input current eventually causes the mirrors to saturate. When using ± 15 V supplies, this occurs at about 10 mA (or ± 2200 V/ μ s). Because signal currents are rarely this large, classical slew rate limitations are absent [6]. According to this characteristic, it can be used as a reverse current conveyer. The bandwidth of CFB is not totally affected by the gain, so there is no need to consider the contradiction between the gain and the bandwidth when designing the circuit.

As shown in Figure 1 and Table 1, it shows a typical AD844 application circuit gain versus bandwidth, from which it can be concluded that the current feedback circuit does not have the concept of constant GBW in the traditional amps. As frequency goes up, GW fluctuates with feedback voltage and feedback resistance, but in general GBW increases with gain.

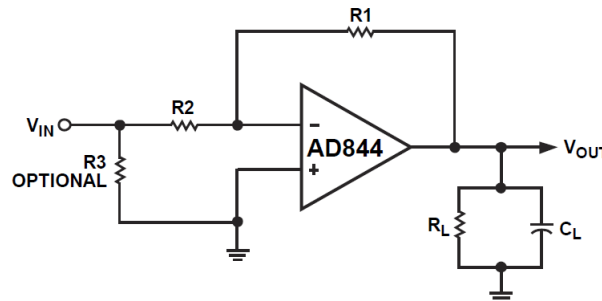


Figure 1. Typical application circuit of AD844 [6].

Table 1. The relationship between AD844 gain and bandwidth [6].

Gain	R1	R2	BW(MHz)	GBW(MHz)
-1	1kΩ	1kΩ	35	33
-1	500Ω	500Ω	60	60
-2	2kΩ	1kΩ	15	30
-2	1kΩ	500Ω	30	60
-5	5kΩ	1kΩ	5.2	26
-5	500Ω	100Ω	49	245
-10	1kΩ	100Ω	23	230
-10	500Ω	50Ω	33	330
-20	1kΩ	50Ω	21	420
-100	5kΩ	50Ω	3.2	320

Based on the current feedback operational amplifier, this paper aims to design a practical wide-band chaotic signal generator of Chua's circuit, and verify the simulation inductance to realize Chua's piecewise linear active resistance. The obtained circuit has good high-frequency response. Then verify the synchronization function when it forms a secure communication circuit and get the phase diagram of its synchronization and non-synchronization. The circuit obtained has strong practical value and application significance, and it can further expand the application of chaos in the field of encryption.

2. Experiment of Chua's Circuit and current Conveyer

Chaos refers to a completely deterministic mathematical model or physical system that does not contain any external random factors. However, its long-term behavior may be extremely sensitive to the change of initial value, with certain randomness and uncertainty. Humans call this phenomenon chaos. Chaotic system is extremely complex and has singularity. Chaos has not yet been unified and deterministic. The existing definitions describe the properties of chaotic motion from the application side, including Li Yorke chaos definition and Lyapunov instability description.

When analyzing and designing a chaotic circuit, if the hardware is realized in an ideal state, it is the analysis state equation. The state equations of common chaotic systems can be divided into discrete realization and continuous realization. The exercise relations and initial conditions of common chaotic systems are shown in the Table 2.

Table 2. Common chaotic system.

System name	System relation	Initial condition
Logistic	$x(n + 1) = 3.7x(n)(1 - x(n))$	$x(0) = 0.32$
Tent	$x(n + 1) = \begin{cases} x(n)/0.4 & x(n) \leq 0.4 \\ (1 - x(n)/0.6) & x(n) > 0.4 \end{cases}$	$x(0) = 0.32$
Chua's	$\begin{cases} dx(t) = ax(t) + ay(t) - \alpha f(x) \\ dy(t) = x(t) - y(t) + z(t) \\ dz(t) = -\beta y(t) \end{cases}$ $f(x) = bx(t) + \frac{1}{2}(a - b)(x + 1 - x - 1)$ $\begin{cases} a = -1.27 \\ b = -0.68 \\ \alpha = 10 \\ \beta = 14.87 \end{cases}$	$\begin{cases} t_{begin} = 0, t_{end} = 1000 \\ \Delta t = 1/3 \end{cases}$ $\begin{cases} x(0) = 0 \\ y(0) = 1 \\ z(0) = 1 \end{cases}$
Chen	$\begin{cases} dx(t) = a(y(t) - x(t)) \\ dy(t) = (c - a)x(t) + cy(t) - x(t)z(t) \\ dz(t) = x(t)y(t) - bz(t) \end{cases}$ $\begin{cases} a = 35 \\ b = 3 \\ c = 28 \end{cases}$	$\begin{cases} t_{begin} = 0, t_{end} = 1000 \\ \Delta t = 1/3 \end{cases}$ $\begin{cases} x(0) = 0 \\ y(0) = 1 \\ z(0) = 1 \end{cases}$
Lorenz	$\begin{cases} dx(t) = a(y(t) - x(t)) \\ dy(t) = rx(t) - x(t)z(t) - y(t) \\ dz(t) = x(t)y(t) - bz(t) \end{cases}$ $\begin{cases} a = 10 \\ b = 8/3 \\ r = 34 \end{cases}$	$\begin{cases} t_{begin} = 0, t_{end} = 1000 \\ \Delta t = 1/3 \end{cases}$ $\begin{cases} x(0) = 0 \\ y(0) = 1 \\ z(0) = 1 \end{cases}$

In general, nonlinear factors need to be introduced into all chaotic system control equations, including limiting and high-dimensional methods. In order to realize a practical chaotic generation circuit, the Chua's circuit is taken as the main research route. Compared with other discrete methods and higher-order methods that need to introduce multipliers, the Chua's circuit forms a third-order autonomous circuit by introducing nonlinear active resistors, which takes advantage of the limiting characteristics of operational amplifiers. The circuit is simple and representative.

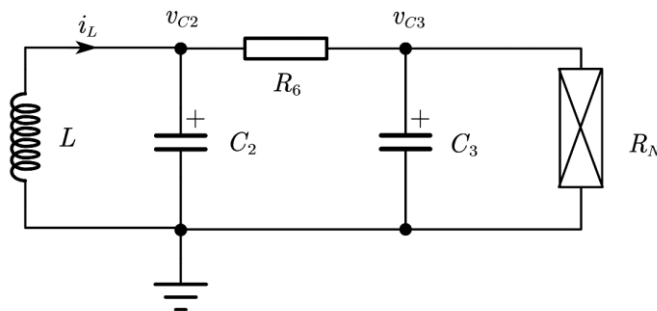


Figure 2. Typical Chua's application circuit.

The typical Chua's circuit is shown in the Figure 2. It is composed of a linear resistor, two linear capacitors, a linear inductor and an active nonlinear resistor called "Chua's diode". The capacitor, the voltage at both ends and the current flowing through the linear inductor are selected as the research

objects. They are taken as the state variables of the circuit equation. According to the circuit topology and parameters, they can be brought into (1), (2) and (3).

$$\frac{dv_{C3}}{dt} = \frac{1}{R_6 C_3} (v_{C2} - v_{C3}) - \frac{1}{C_3} f(v_{C3}) \quad (1)$$

$$\frac{dv_{C2}}{dt} = \frac{1}{C_2} i_L + \frac{1}{R_6 C_2} (v_{C3} - v_{C2}) \quad (2)$$

$$\frac{di_L}{dt} = -\frac{1}{L} v_{C2} \quad (3)$$

$f(x)$ is a nonlinear function, and E is the absolute value of the turning voltage of the nonlinear resistance, which is expressed in a dimensionless form:

$$f(x) = \begin{cases} bx + (b - a)E, & x < -E, \\ ax, & -E \leq x \leq E, \\ bx + (a - b)E, & x > E, \end{cases} \quad (4)$$

The above equations are ordinary differential equations without time variables at the right end of the equation, forming a third-order autonomous system, and the state variables form a three-dimensional phase space. Normalize the above equations according to the actual circuit, and take $x = \frac{v_{C3}}{E}$, $y = \frac{v_{C2}}{E}$, $z = \frac{R_6 i_L}{E}$, $\tau = \frac{t}{R_6 C_2}$, $a = R_6 G_a$, $b = R_6 G_b$, $\alpha = \frac{C_2}{C_3}$ and $\beta = \frac{C_2 R_6^2}{L}$. Where is the subsection conductance of the nonlinear resistance, and the normalization equation is finally obtained as

$$\frac{dx}{d\tau} = \alpha(y - x - f(x)), \quad (5)$$

$$\frac{dy}{d\tau} = x - y + z \quad (6)$$

$$\frac{dz}{d\tau} = -\beta y \quad (7)$$

Chua's circuit has been widely used in practical circuits. However, the bandwidth of Chua's circuit based on voltage feedback is always limited due to the bandwidth limitation and slew rate limitation of voltage feedback operational amplifier and the characteristics of many external components.

In this paper, the key to improve the circuit is to use the current feedback operational amplifier to improve the total bandwidth of the circuit and make up the current conveyer. Current conveyer is one of the most commonly used active components in current mode circuit. Its function is similar to that of operational amplifier in voltage mode circuit. However, current conveyer has good high-frequency performance and strong versatility and flexibility.

The current conveyer is divided into the first generation current conveyer CCI, the second generation current conveyer CCII and the third generation current conveyer CCIII. In the discrete original circuit, often use the second-generation current conveyer.

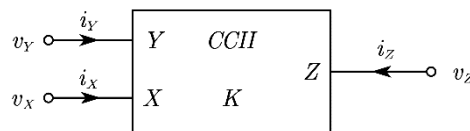


Figure 3. Current conveyer.

In Figure 3, the voltage current relationship is:

$$\begin{cases} i_Y = 0 \\ v_X = v_Y \\ i_Z = K i_X \end{cases} \quad (8)$$

where v_X i_X are the voltage and current of the X node respectively, and v_Y i_Y v_Z i_Z are analogized to obtain the transmission performance of the current conveyer. K is the transmission coefficient of the current conveyer. When $K = 1$ it is the forward current conveyer; when $K = -1$ it is the inverting current conveyer. When the current conveyer is implemented in hardware, the current

feedback operational amplifier AD844 with TZ node is required. The circuit shows in Figure 4. The TZ node is the output of the first stage current mirror, and the output current is equivalent to the current at the reverse node. The resistance of the input base of the second stage is very large, up to M Ω , to realize the conversion of current and voltage to output voltage. The load capacity of the TZ node is poor, so if the TZ node is used to output current, a first-level buffer needs to be added before the non-inverting terminal input. Based on the TZ node, the inverting current conveyer can be designed by two AD844.

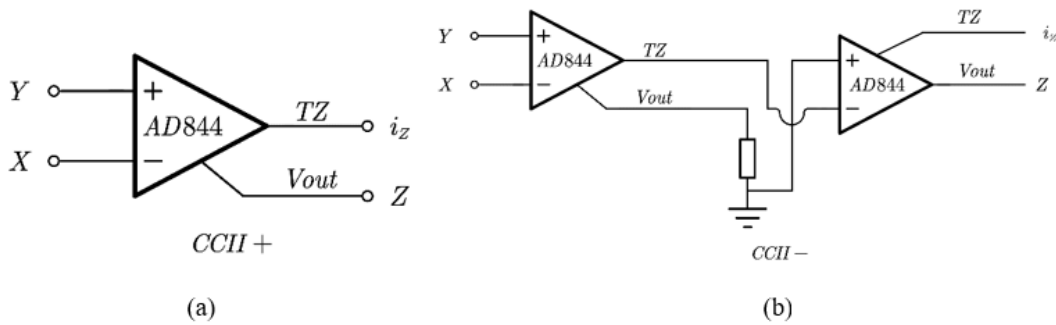


Figure 4. Current conveyer. (a)Forward current conveyer. (b) Inverting current conveyer.

The implementation circuit is shown in the above two figures. According to the current conveyer, a segmented resistance load can be formed to form a Chua’s diode.

3. Application Analysis of current Conveyer

The sectional resistance required by Chua's circuit can be realized by a current conveyer. A three-stage piecewise linear resistor can be realized by using a forward current conveyer. The circuit diagram and the volt-ampere characteristic diagram of the piecewise linear resistor are shown in Figure 5.

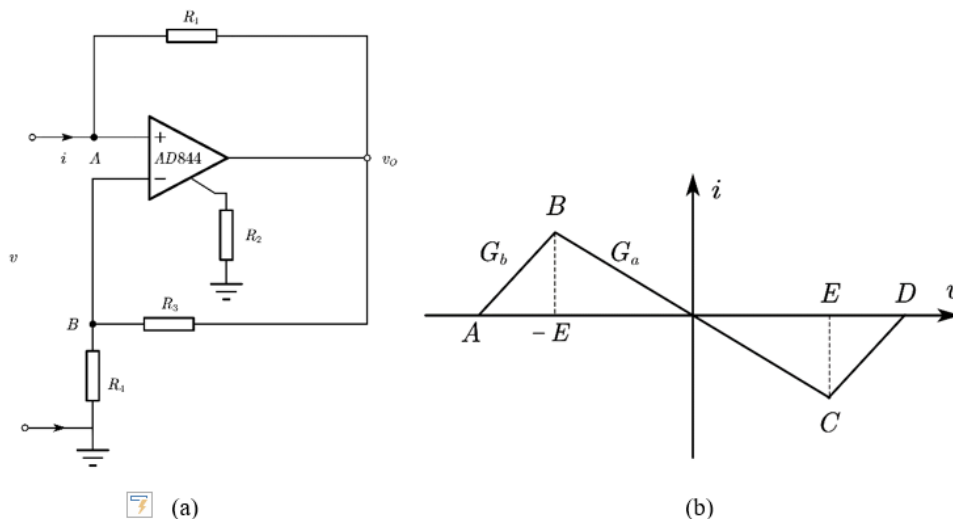


Figure 5. Segmented resistance circuit composed of AD844. (a)Transfer characteristics of Piecewise Linear Resistance. (b)Realization of three-stage segmented Resistance based on AD844.

When the input voltage V of the circuit is in the range of (-E, E), the current conveyer composed of the current amplifier at this time is in the linear amplification area. When $R_1 = R_3$, the current voltage relationship is as follows by the "virtual short and virtual break" effect of the operational amplifier and KCl and KVL:

$$\frac{v}{i} = \frac{v}{I_{R_1}} = \frac{v}{\frac{v-v_O}{R_1}} = \frac{R_1}{1-\frac{v}{v_O}} = \frac{R_3}{1-\frac{v_O}{v_B}} \quad (9)$$

$$= \frac{R_3}{1 - \frac{R_3 + R_4}{R_4}} = -R_4 \quad (10)$$

When the input voltage operates in the linear region, it corresponds to the BC segment shown in the left figure. At this time, the slope is $-\frac{1}{R_4}$. When the input voltage exceeds the turning voltage E, it corresponds to the AB and CD segments shown in the left figure. At this time, the slope is $\frac{1}{R_1}$. Due to the conductivity characteristics of the current conveyer, different sectional resistances can be connected in parallel, and the conductivity coefficients can be correspondingly superimposed to obtain more complex sectional resistances. Figure 6 shows the five-stage segmented circuit.

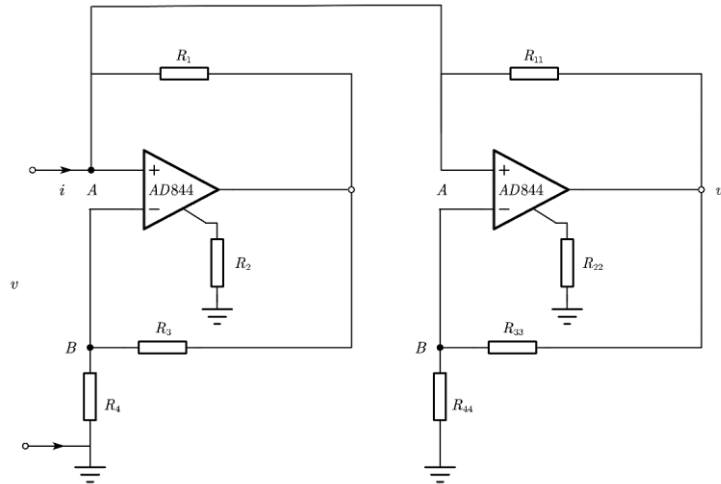


Figure 6. Realization of five-stage segmented Resistance based on AD844.

$$i = f(v) = \begin{cases} G_c v - (G_b - G_c)E_b - (G_a - G_b)E_a, & v < -E_b \\ G_b v + (G_a - G_b)E_a, & -E_b \leq v < -E_a \\ G_a v, & -E_a \leq v \leq E_a \\ G_b v + (G_a - G_b)E_a, & E_a < v \leq E_b \\ G_c v - (G_b - G_c)E_b - (G_a - G_b)E_a, & E_b < v \end{cases} \quad (11)$$

Among the given segmented resistors, Chua's chaotic circuit mainly works in the negative resistance interval near the origin. When multiple segmented resistors are connected in parallel, the resistance can be closer to the ideal turning state, and the circuit keeps stable in the chaotic state. When connected in parallel, t Segmentation is based on the transition voltage E of each part in the circuit, and the calculation formula of the turning voltage E of the circuit is

$$E = \frac{R_4}{R_4 + R_3} \quad (12)$$

In the existing research, the application of parallel multi-stage Chua's negative resistance has been verified, but most of them are realized by changing the voltage value of VCC and supplying multiple different VCCS, such as 12V and 5V, to the signal source. The signal source needs additional DC-DC conversion device [7].

There are also documents that propose a single power supply mode. Considering the actual application, this paper selects AD844 with a supply voltage of Positive and negative 18V to change the turning voltage by changing the resistance value. Figure 6 and 7 show a complete circuit and its simulation results. In the circuit, $L_1 = 68\mu H$, $C_1 = 30pF$, $C_2 = 220pF$, $R_1 = 1240\Omega$, or $\alpha = 7.33, \beta = 5$. Adjusting R_8, R_{16} can improve the phase diagram roll size of the circuit.

From the simulation results, the phase diagram and time-domain waveform diagram of Chua's circuit designed with the current transmitter are very clear, and the spectrum has strong selectivity. The circuit has entered a chaotic state, and a pair of chaotic attractors appear corresponding to it, namely "The Double Scroll", indicating that the parameters of the designed circuit are valid.

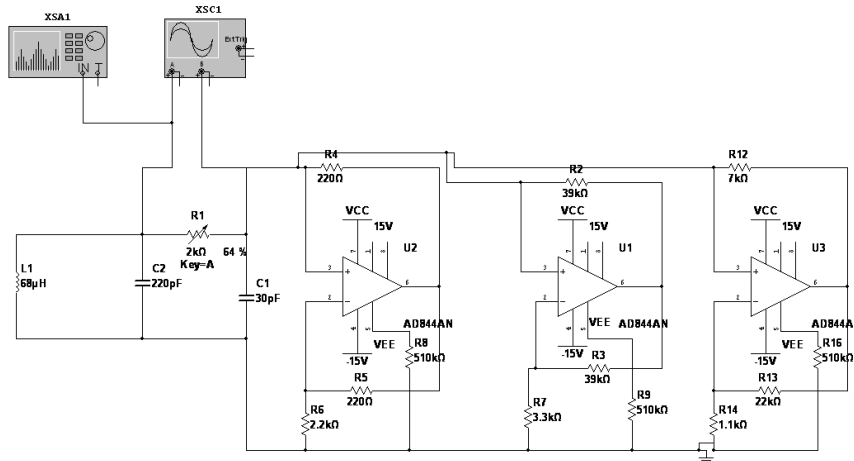


Figure 7. Simulation of chaotic Circuit in Multisim.

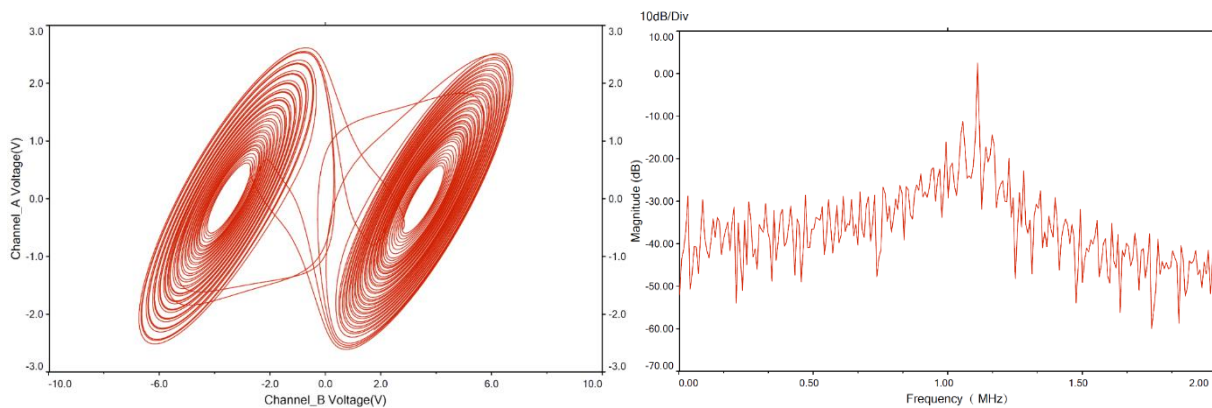


Figure 8. Multisim Simulation Results. (a) $v_{C2} - v_{C1}$ phase diagram (refresh time 10ms). (b) Chaotic signal spectrum diagram.

4. Design of Broadband Active Inductor

With the development of integration technology, people put forward higher requirements for the integration of circuits. With the integration of resistance, capacitance and operational amplifiers, integrated circuit researchers have gradually begun to pay attention to the realization of simulation inductors. Broadly speaking, all models whose impedance increases with frequency can be considered to be active simulated inductors to a certain extent. The earliest active inductance model was 1964 B. Christensen proposes that the capacitance on the transistor collector will reduce the gain at high frequency and weaken the Miller effect of the feedback resistance, thus improving the input impedance, which can be regarded as linear active inductance in a certain range. With the deepening of the research, there are many practical inductance design, including Riordan simulated inductor, Gyro simulation inductance, according to the use can also be divided into floating ground simulation inductance and grounding simulation inductance and so on [8,9].

Operational amplifiers, current conveyers and transconductance are often selected to form active inductors. From the practical point of view, this paper will analyze the broadband grounding simulation inductance in order to obtain better application in the required chaotic circuit. In current applications, grounding simulation inductors are mostly used in filters and various signal processing circuits, but the current active inductors still focus on the continuous time linear equalizer (CTLE) of wired receiver. Active inductors are also widely used in broadband output drive to generate shunt peaks, thus expanding the bandwidth of amplifiers. However, there are still some gaps in the research of broadband simulated inductors [10].

In this paper, a broadband grounding active simulated inductor is proposed based on impedance converter and current conveyer.

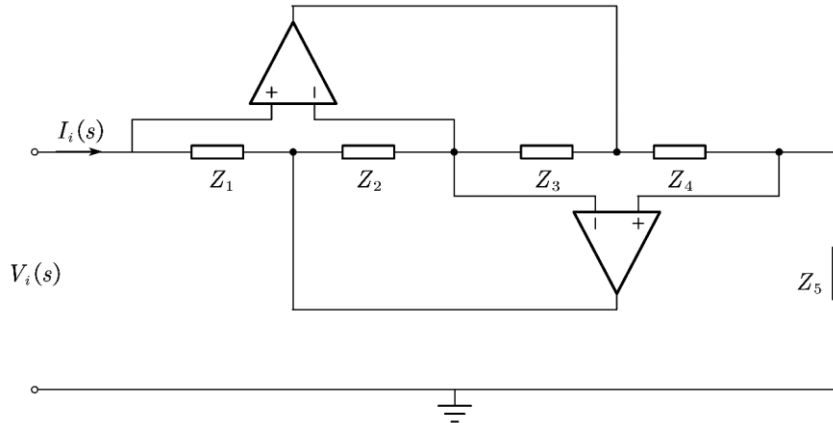


Figure 9. Operational amplifier simulated inductance.

Figure 9 shows a general impedance converter. The impedance of the simulation is

$$Z_i = \frac{V_i(s)}{I_i(s)} \tag{13}$$

When the operational amplifier is in the ideal state, the Q value of the inductance is infinite, and the input impedance of the converter can be deduced from the impedance transformation (where the impedance is the transformed complex impedance).

$$Z_i = \frac{V_i(s)}{I_i(s)} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4} \tag{14}$$

Select Z2 as capacitance C2, and the impedance can be expressed as

$$Z_i = \frac{R_1 R_3 R_5 C_2}{R_4} \tag{15}$$

The output characteristics of impedance can be studied by using the AC scanning function of Multisim. Taking the ideal inductance as an example, the ideal current source is selected as the input to analyze the output complex impedance under different frequency responses.

According to the results of AC scanning, we can get the value of simulated inductance in a specific interval, for example, in the right figure, select the magnitude-frequency curve to calculate its slope.

$$L = \frac{Z}{2\pi} = \frac{1}{2\pi} \frac{dy}{dx} = 10mH \tag{16}$$

It is proved that it accords with the theoretical value of ideal inductance. Therefore, this method can be used to analyze the frequency response of active inductor.

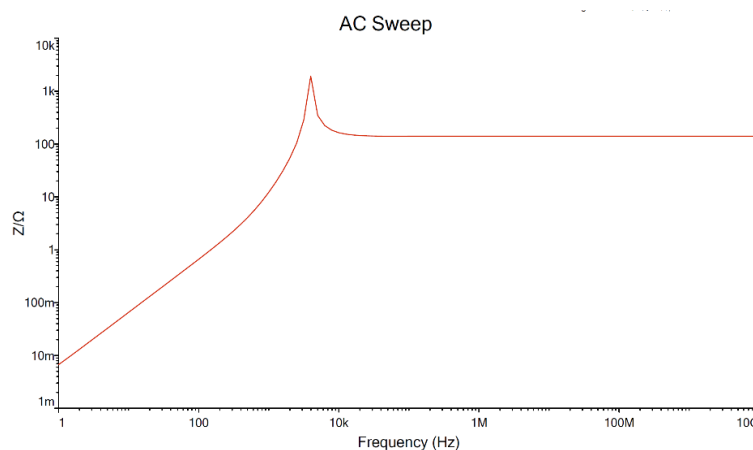


Figure 10. Frequency response of active simulated inductor based on $\mu A741$.

The operational amplifier in the impedance conversion circuit is replaced by $\mu A741$, and then the simulation is carried out again. Take $Z_1 = 10\Omega, Z_2 = 1000\Omega, Z_3 = 10\Omega, Z_4 = 1mF, Z_5 = 10\Omega$. According to the output impedance formula given above, the theoretical output impedance is $1mH$, and its simulation is shown in the Figure 10.

Because of the nonlinear and unsatisfactory characteristics of the actual operational amplifier, the linear range of the impedance converter is only in the range of. There are two key points in the design of broadband simulated inductor, including the realization of small impedance accurate inductance and the realization of broadband inductance.

When OPA827 is used as an alternative op amp, its characteristics are still not improved, and the linear bandwidth is still at a low level. Simulation shows that the bandwidth of the impedance converter composed of voltage feedback operational amplifier is always at the low frequency level. The simulated inductor with current feedback has great advantages over the simulated inductor with operational amplifier mode. The current mode circuit has many advantages, such as low voltage, low power consumption, low noise and so on, which has attracted the attention of researchers. Next, based on the $CCII$ to implement analog circuit. The voltage amplifier is constructed of $CCII -$ and the current amplifier is constructed of $CCII +$ in Figure 11.

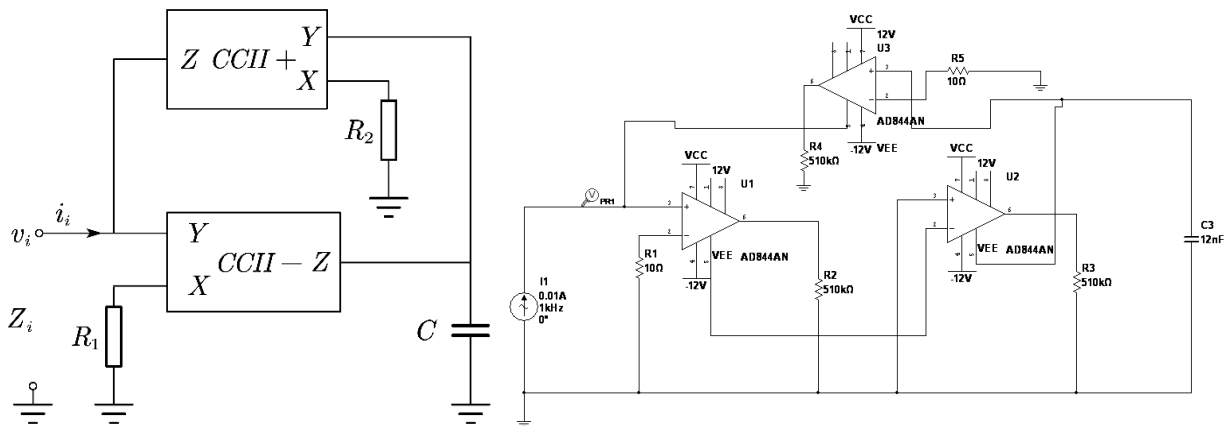


Figure 11. Active inductor composed of current conveyer and its circuit realization.

(a)The grounded simulated inductors using current conveyer. (b)AD844 active inductor circuit based on current conveyer.

According to the port characteristics of the current conveyer, it can be deduced that the inductance of the circuit is

$$L = R_1 R_2 C \tag{17}$$

According to the previous AD844 characteristics, AD844 can be regarded as a $CCII +$ current conveyer, which can form a $CCII -$ current conveyer, otherwise it is not possible. The circuit composed of AD844 shows in Figure 11, and its linear interval can be obtained by simulation in Figure 12.

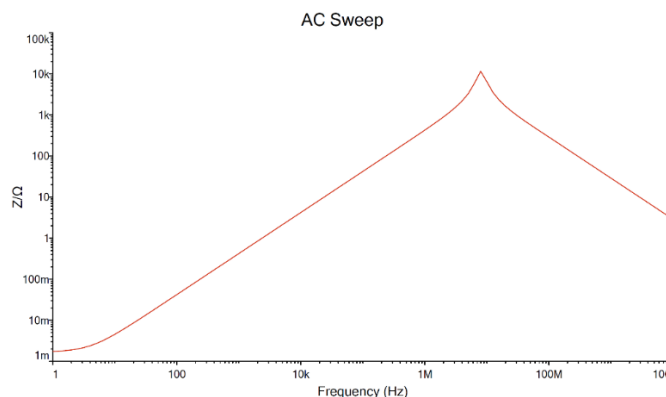


Figure 12. Frequency response of active inductor based on current conveyer.

In this circuit, the resistance of simulated inductor is mainly determined by R_5 and C_3 , and the bandwidth can be adjusted by changing the resistance of R_1 .

It can be seen from the graph that the width of the linear interval has reached 7M Hz and above, and the interval with a change of less than 5% is generally taken as the main linear working interval. Because the TZ node of AD844 is not ideal, the load capacity is very weak, and because $CCII -$ needs two AD844, the influence of non-ideal factors of the two current conveyers is not the same. Therefore, the selection of parameters is not fully in line with the ideal state. In this paper, we do not theoretically explore the influence of non-ideal factors of circuits, according to V. G. Rydin, the non-ideal factor is controllable [11].

As the number of AD844s is increased, its impedance also follows the parallel principle, but the operating bandwidth does not change significantly.

5. Overall Design

5.1. Design of Broadband active inductor

When using linear passive resistance, the main function of operational amplifier is to form Chua's diode. If AD844 is used, it is necessary to keep its TZ node in a state of high resistance to the ground. According to its principle, the AD844 can be replaced with the current feedback operational amplifier without TZ output, and the THS3061 series with higher slew rate can be selected to further expand the bandwidth. Circuit shows in Figure 13.

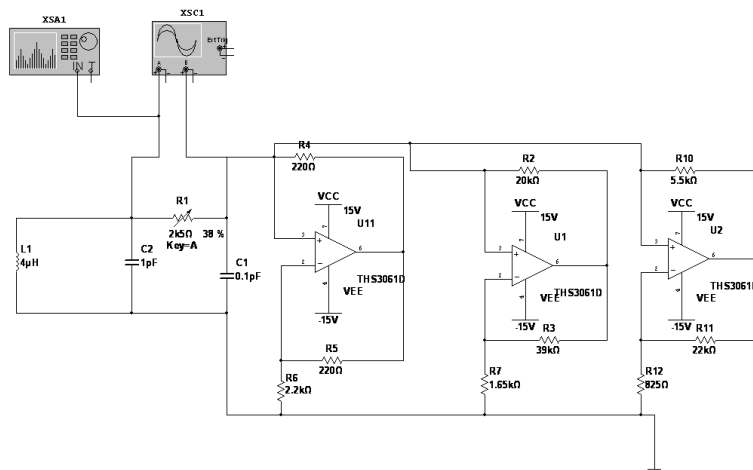


Figure 13. Design of Broadband chaotic Circuit.

As shown in Figure 14 and 15, due to the non-ideal factors of operational amplifier and the further improvement of working frequency, including offset voltage, α and β don't fully follow the results of theoretical analysis. In this paper, an empirical test result is given.

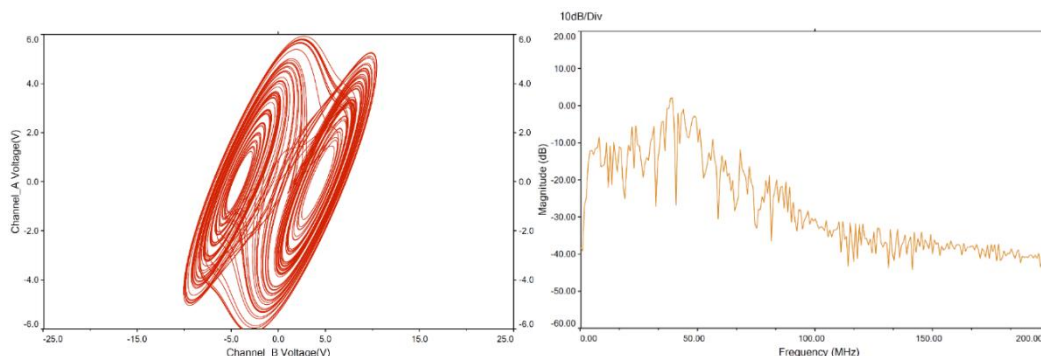


Figure 14. Multisim Simulation Results. (a) $v_{C2} - v_{C1}$ phase diagram (refresh time 100us).(b) Chaotic signal spectrum diagram.

By changing the parameters of the left chaotic loop, the control parameters of the governing equation can be changed. With the further increase of operating frequency, not only need to change the control parameters, but also need to change the parameters such as G_a in the nonlinear equation, and its physical meaning is conductance in the circuit. With the increase of the operating frequency, the conductance of the working interval of the chaotic circuit needs to be increased proportionally.

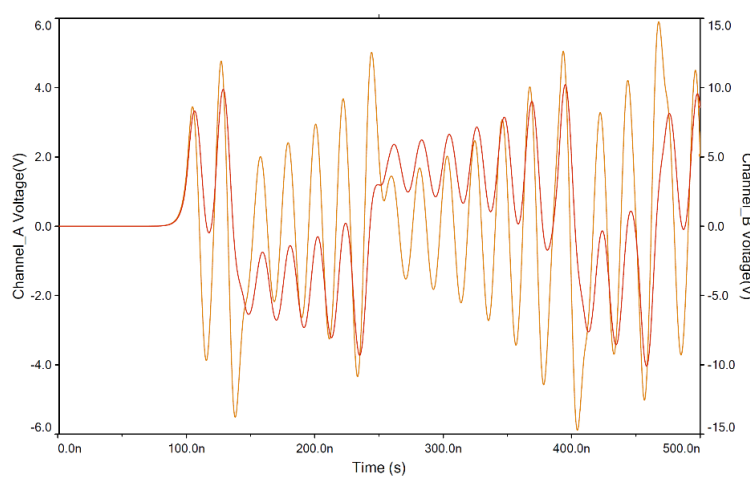


Figure 15. Vibration initiation process of chaotic circuit.

When the working frequency is high, due to the initial value sensitivity of differential, chaotic circuit loop may not self-start, or the vibration initiation time is too long. At this time, it is necessary to adjust the resistance value to make it appear the limit cycle, and then adjust it to a single focus to ensure the circuit vibration. The starting process is as shown in Figure 15.

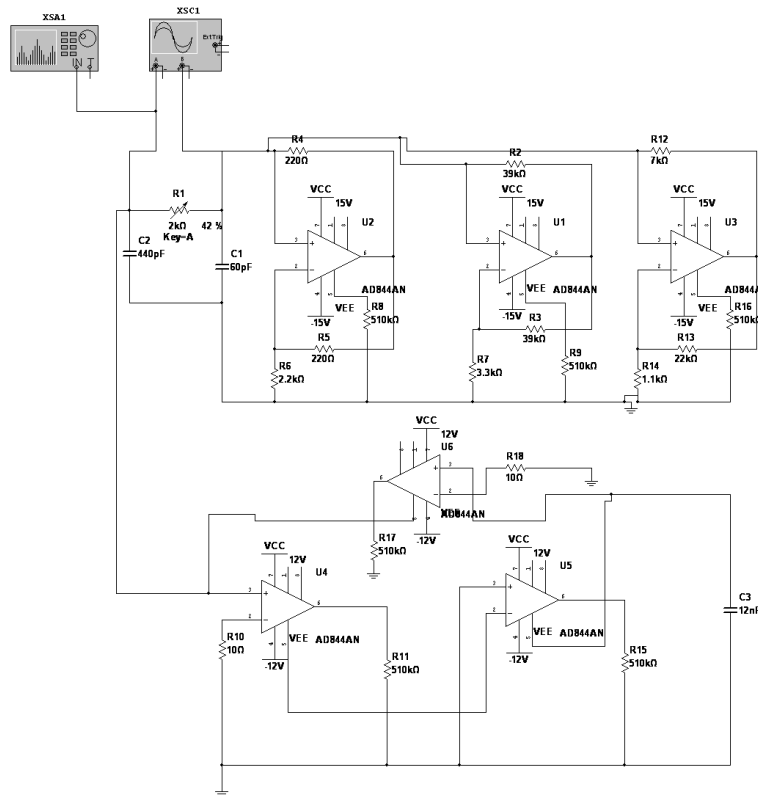
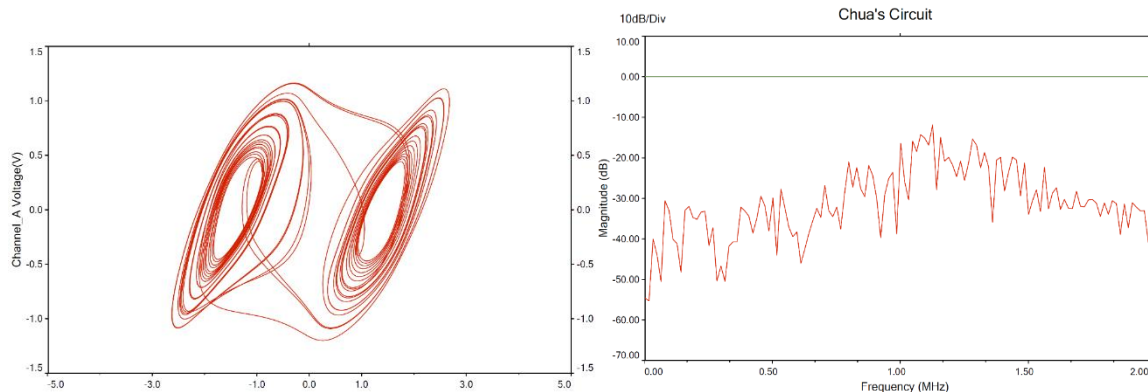


Figure 16. Chaotic Circuit with active inductor.

By replacing passive inductor with active simulated inductor, the working frequency of passive inductor needs to be reduced by an order of magnitude due to bandwidth limitation.



(a) $v_{C2} - v_{C1}$ phase diagram (refresh time 100us). (b) Single channel spectrum diagram.

Figure 17. Multisim Simulation Results.

Compared with passive inductors, the Q value and impedance characteristics of simulated inductors are not ideal, and the spectrum selection is not strong.

5.2. Circuit application-- application of chaotic circuit in signal encryption

With the development of information security technology, people pay more and more attention to the security and encryption of information. In recent years, with the rapid development of chaos theory and application, mixed capital cryptography has made great progress. Researchers have put forward many encryption theories based on chaos theory. Since the British mathematician Matthews put forward chaotic encryption in 1984, the design of encryption system using high-order stochastic chaotic systems has made great progress. Chaotic encryption signals need to make full use of the sensitive dependence of the system on initial values and parameters, chaotic sequences are used for encryption, the key space is large, it is not easy to predict. By using the sum of the pixel values of the original image as the secondary key, the difficulty of enumeration method can be increased, thus ensuring the security of the system itself.

In the current chaotic encryption system, how to ensure that the chaotic system at the conveyer and receiver has the same initial value is the key problem of chaotic decryption. The chaotic synchronization of discrete systems can be well realized, but the chaotic synchronization of simulation systems has higher confidentiality. Next, the chaotic synchronization function of the original wide-domain active simulated inductance chaotic circuit is verified based on the above original wideband active simulated inductance chaotic circuit design. Synchronization circuit shows in Figure 18 and 19.

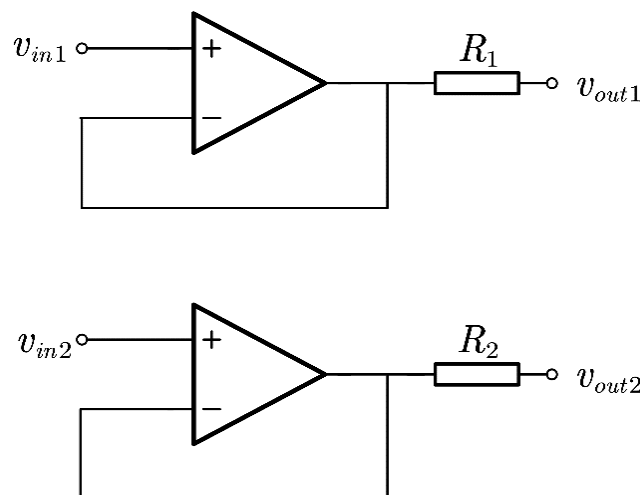


Figure 18. Chaotic feedback synchronization circuit.

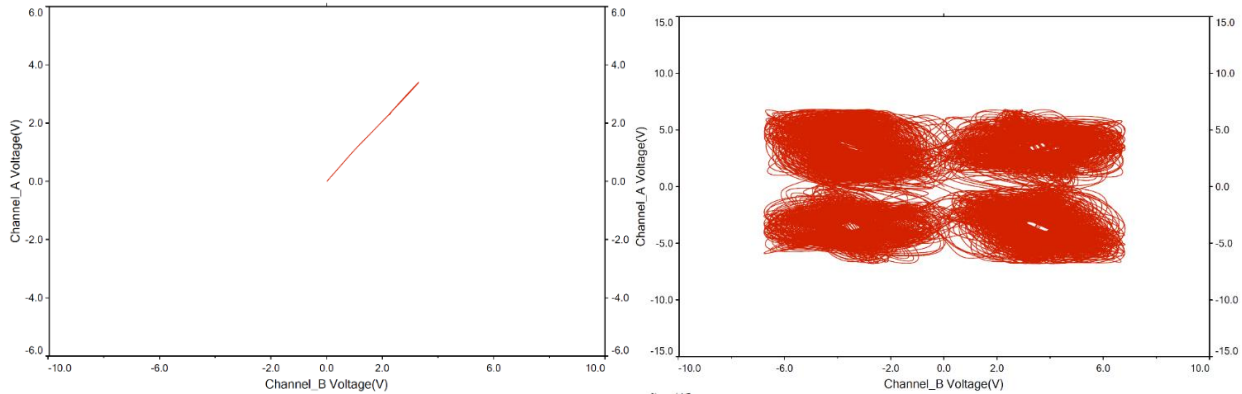


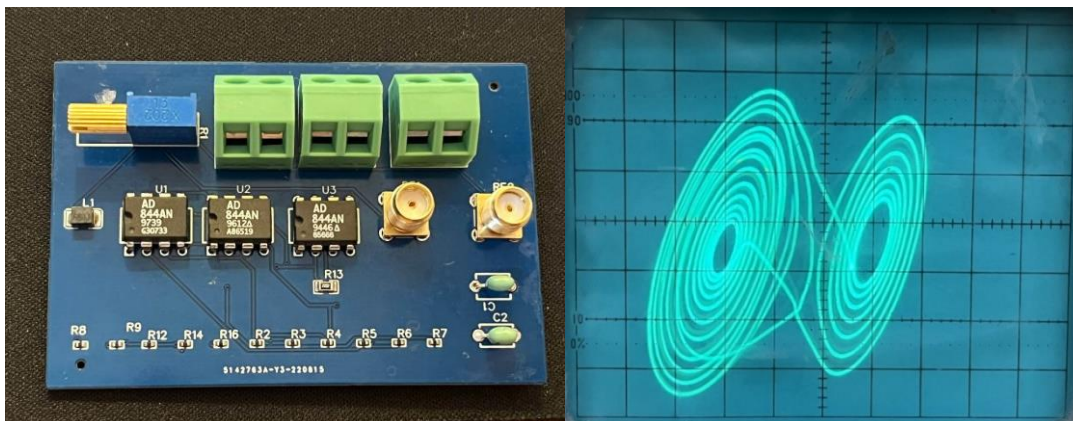
Figure 19. Synchronous simulation. (a) Synchronized. (b) Not synchronized.

6. Physical Circuit and Debugging

The hardware implementation is shown in the Figure 20. The finalized circuit realization circuit is shown in Figure 13, which is realized through PCB, as shown in the figure. In the process of debugging, it is necessary to adjust the potentiometer to the minimum first, and then adjust the potentiometer to the maximum after the stable limit cycle appears. After the screen has no waveform, when it is guaranteed to be in double-scroll, slowly reduce the resistance of the potentiometer to obtain different waveforms.

Many problems were found in the actual circuit debugging. If the positive and negative power supply voltages are asymmetric, the attractor will be asymmetric in the double-scroll, and the input offset voltage will also have a great influence on the Lissajous figures, which will cause the attractor to shift. And it is not possible to simply replace the actual inductance with the same impedance simulated inductance. When the equivalent resistance of the simulated inductance is large to a certain extent, the circuit will not produce chaos. In addition, the board consumption is also worth noting. It is recommended to use Electroless Nickel/Immersion Gold (ENIG) process and pay attention to the wiring.

Due to the sensitivity of chaotic circuits, the joint control effect of an analog oscilloscope and a spectrum analyzer is the best during debugging. The vertical resolution of analog oscilloscopes is high, continuous and infinite, while the resolution of digital oscilloscopes is generally only 8 to 10 bits. The analog oscilloscope can also realize real-time bandwidth and real-time display: the single-shot waveform has the same bandwidth as the continuous waveform, and the bandwidth of the digital oscilloscope is closely related to the sampling rate. It is easy to confuse phase diagrams in chaotic circuits. The spectrum analyzer simultaneously observes the spectrum peaks, making them the steepest.



(a) Physical PCB implementation. (b) Observation of phase diagram by analog oscilloscope.

Figure 20. Physical circuit and test results.

7. Conclusions

In this paper, the design paradigm of chaotic circuit is summarized, and the design mode of digital and analog circuit is analyzed. Based on the current conveyer, a design of analog unintegrated Chua's circuit is proposed.

In chaotic communication, the higher the frequency of chaotic signal as carrier signal, the higher the efficiency of modulation signal transmission signal. Because of the dynamic characteristics and initial value sensitivity of chaotic circuit, it is difficult for the codebreaker to crack the communication information completely and consistently when the high frequency chaotic signal is transmitted as carrier signal. Therefore, improving the working frequency of chaotic circuits is an important research direction, and has a wide range of application scenarios.

In the design, the current conveyer current conveyer is widely used as an active original, and the current feedback operational amplifier has the advantage of not being affected by the gain band width product with good high frequency characteristics. With the increase of working frequency, the inductance is required to be more and more high, and then the active inductance is introduced. Its port characteristics are stable, according to its idea, it can also promote the integration of chaotic circuits. Compared with the Riordan simulated inductor composed of amplifiers, the high frequency characteristics of active inductor based on AD844 are excellent. At the same time, based on the second-generation current conveyer, Chua's diode and other circuits are designed.

In this paper, a non-integrated wide-domain chaotic signal generator circuit based on active inductor is proposed, and the theoretical modeling and numerical simulation are carried out. The AD844 chip developed by ADI Company can be used as $CCII +$ current conveyer, and then it is used to form $CCII -$ current conveyer. In this paper, a practical circuit based on AD844 is proposed, and the bandwidth of chaotic carrier signal can reach 5M Hz. At the same time, the chaotic synchronization function is verified to ensure its practicability in chaotic secure communication circuit.

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