Progress In Electromagnetics Research, PIER 75, 225–237, 2007

A NEW ARCHITECTURE OF UWB RADAR UTILIZING MICROWAVE CHAOTIC SIGNALS AND CHAOS SYNCHRONIZATION

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Abstract—In this paper, we present a new scheme for the realization of a wide-band chaotic RADAR system. The remarkable characteristics of such scheme are: (1) Wide-band chaotic signal generated from microwave chaotic Colpitts oscillator is directly used as the RADAR signal; (2) Chaos synchronization is used to recover the chaotic signal from the back-scattered signal by targets; (3) The intrinsic sensitivities of the chaotic signal to the parameters of the chaotic circuit and to the initial conditions are used to realize the "multi-user" property. System simulations show that such RADAR can still work in an environment when the signal-to-noise ratio (SNR) is lower than $-20\,\mathrm{dB}$.

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1. INTRODUCTION

RADAR, abbreviated from "Radio Detection and Ranging", might be the most important technical invention of human in the area of microwave engineering. From the invention of a primitive anti-collision marine RADAR by a Germany Christian Husmeyer in 1903, RADAR has gone through a history for more than 100 years. With the rapid development of microelectronics and advanced manufacturing technics from 1960s, new techniques are continuously applied in various RADAR systems [1–3].

Nowadays, modern RADAR systems have been regarded to be very "mature" in all the aspects like performance, manufacturing technics and reliability, and have been widely applied in either military and civil uses. However, the development of RADAR is far from its end. The coming forth of the "electric war" and the issues of the electromagnetic compatibility (EMC) raised new requirements to RADAR systems. For military RADAR, it would be better if the RADAR signal is more difficult to be detected or interfered, while for civil RADAR, EMC performance is more emphasized. A typical example is the anti-collision vehicle-borne RADAR: since the vehicle-borne RADAR on one car can not avoid the luminance from the adjacent lane, it has to work under the interference in a same frequency band. The number of cars is innumerous, meaning that for a vehicle-borne RADAR, it has to be co-existent with a number of RADARs with the same schemes, or it should be with the property of "multi-user", similar to a large-volume wireless communication system, such as a cellular system. The key requirement for modern military and civil RADARs is actually the same, i.e., how to let RADAR signals look more like wide-band noise. As the spread-spectrum technique has been widely used in military and civil communications, using ultra-wide band, noise-like signals in modern RADAR systems is also a trend.

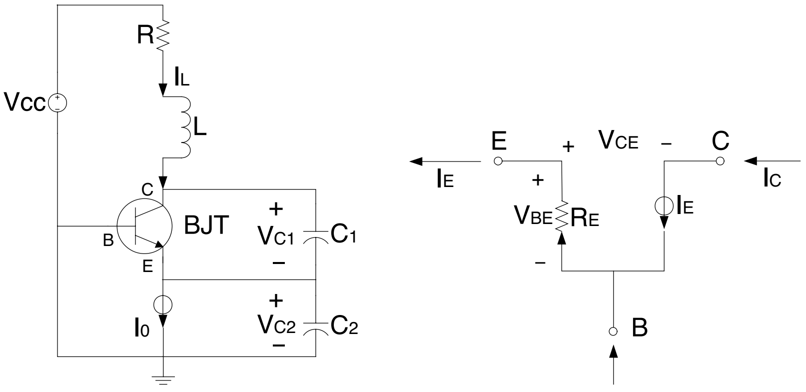
In recent years, chaos has been applied in various communication systems. In 2005, a chaos-based communication system at high bit rates using commercial fibre-optic links has been reported in [4, 5]. For radar systems using chaotic signals or pesudo random signals, there are also several literatures published [6–11]. In this paper, we present a new scheme for the realization of a wide-band RADAR using chaos. Different from those published literatures listed above, the characteristics of this new scheme are: (1) Wide-band signal generated from microwave chaotic circuits is directly used as the RADAR signal; (2) Chaos synchronization is used to recover the chaotic signal from the back-scattered signal by targets, based on the ideas in [12–14]; (3)

The intrinsic sensitivities of the chaotic signal to the parameters of the chaotic circuit and to the initial conditions are used to realize the "multi-user" property. By utilizing microwave chaotic RADAR signal and using chaos synchronization, such a RADAR scheme is different for known RADAR schemes, and is with some unique characteristics.

The paper is organized as following: (1) Deterministic chaos and microwave chaotic circuits are briefly introduced; (2) The new chaos based RADAR scheme is described; (3) System simulations are run to illustrate how the system works; (4) A brief discussion is given.

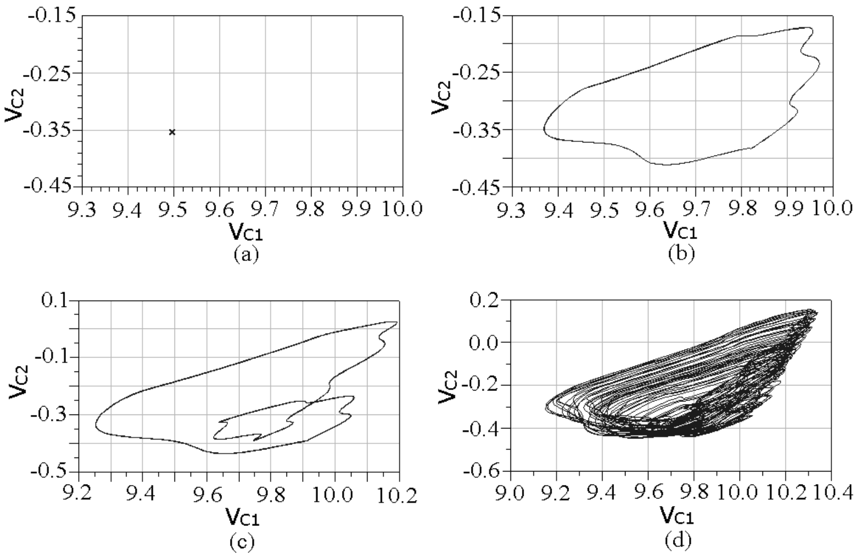
2. MICROWAVE CHAOTIC CIRCUITS

Deterministic chaos has been widely studied in various scientific areas, especially in circuits and systems. It has been known that deterministic chaos can be described by definite dynamic equations but still with un-predictable long term behaviors. Chaos is a status different from the equilibrium, period or quasi-period of a dynamic system. Chaotic signals generated by chaotic circuits exhibit noise-like waveforms in time domain and continuous spectra in frequency domain. Different from real noise, chaotic signals can be controlled or synchronized. So far, various chaotic circuits and systems have been extensively studied to illustrate the evolution from DC to chaos. One typical example is the famous Chua's circuit. In early researches, chaotic circuits realized in laboratory only generated chaos spectra with kilohertz to megahertz bandwidth, but till now, chaotic Colpitts circuits operating at microwave frequencies have been reported [15, 16].



(a) (b)

Figure 1. (a) Colpitts circuit and (b) Equivalent circuit model of the BJT in (a).



(a) (b) (c) (d)

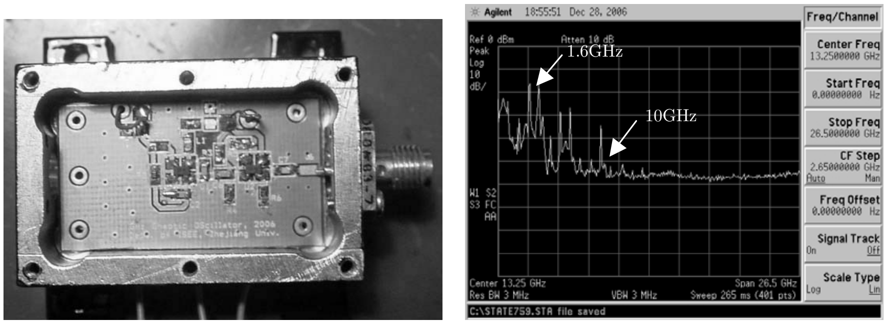
Figure 2. Bifurcations in Colpitts circuits. (a) Equilibrium (DC), $R = 100\,\text{Ohm}$; (b) Periodic oscillation, $R = 50\,\text{Ohm}$; (c) Quasi-periodic oscillation, $R = 35\,\text{Ohm}$; (d) Chaotic oscillation, $R = 27\,\text{Ohm}$.

Fig. 1(a) shows a Colpitts circuit realized by a bipolar junction transistor (BJT), which might be the most common oscillator widely used from very low frequencies to millimeter wave frequencies. Being a single-transistor circuit with inherent nonlinearity, Colpitts circuit has the potential to generate high frequency chaos [17]. Colpitts circuit in Fig. 1(a) can be described by following circuit equations:

$$\begin{aligned} C_1\frac{dV_{C_1}}{dt} &= -f(-V_{C_2}) + I_L \\ C_2\frac{dV_{C_2}}{dt} &= I_L - I_0 \\ L\frac{dI_L}{dt} &= -V_{C_1} - V_{C_2} - I_L R + V_{CC} \end{aligned} \tag{1}$$

where $(f\cdot)$ is an exponential function representing the nonlinearity term of the BJT Model shown in Fig. 1(b) [18]. By such circuit equations, the status of a Colpitts oscillator can be calculated for different circuit parameters, i.e., capacitance C_1, C_2, inductance L and resistance R. In Fig. 2, typical attractors and the so-called "bifurcations" of a Colpitts oscillator are presented, which are obtained with a professional RF and microwave circuit simulator, Agilent's Advanced Design System (ADS). The BJT used in simulation is Philips' BFG425W with a threshold frequency of 25 GHz and the circuit parameters are $C_1 = 5\,\mathrm{pF}$, $C_2 = 5\,\mathrm{pF}$, $L = 6\,\mathrm{mH}$, $I_0 = 5.26\,\mathrm{mA}$ and $V_{CC} = 10\,\mathrm{V}$. We see that with the variation of the resistance R from 100 Ohm to 27 Ohm, the Colpitts oscillator experiences sequentially the equilibrium, periodic, quasi-periodic and chaotic status. We see that in the case of chaos, the Lissajous pattern formed by V_{C1} and V_{C2} constructs the so-called "strange attractor", in which trajectory never intersects with itself, corresponding to a non-periodic oscillation.

The design and realization of high frequency Colpitts oscillator with predetermined spectrum bandwidth have been presented in detail in [16, 19]. The latest realization of microwave chaotic has reached microwave X-band. Fig. 3(a) shows a microwave chaotic Colpitts oscillator in a module form, and Fig. 3(b) shows the output spectrum from the module. We see from Fig. 3(b) that the fundamental frequency of the Colpitts oscillator is up to about 1.6 GHz, and the discriminable continuous spectrum is extended to 10 GHz, indicating that although Colpitts circuit is with a simple structure, it can indeed generate ultra-wide band continuous spectrum. The random characteristics of the output chaotic signal have been analyzed in Ref. [20]. In this paper, we will try to utilize such ultra-wide band chaotic signal as RADAR signal.



(a) (b)

Figure 3. (a) Microwave chaotic Colpitts oscillator module; (b) Measured power spectrum of output chaotic signal.

3. SYNCHRONIZATION OF CHAOTIC SIGNALS

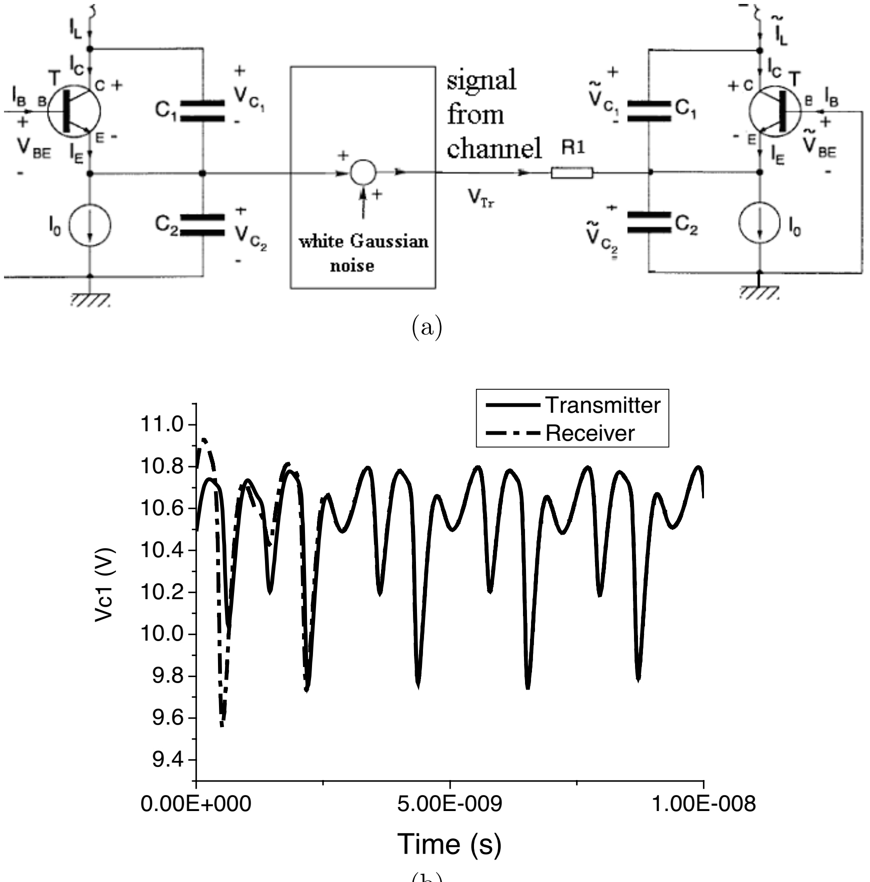
Chaotic signals are controllable and synchronizable, which make them different from "real" noises. Chaos synchronization is always a hot topic in nonlinear science community, and plays an important role in chaotic communications because it offers a potential advantage over non-coherent detection in terms of noise performance and data rate when the information is recovered from a noisy distorted signal [21]. There are several kinds of chaos synchronization, such as identical synchronization and phase synchronization. In most cases the identical synchronization is used in chaotic communication. Generally there are two synchronization schemes for identical synchronization: Pecora-Carroll (or drive-response) synchronization [22] and error feedback synchronization which is based on nonlinear observer method [23, 24]. The synchronization performance comparison of chaotic colpitts oscillators using the two schemes have been discussed in Ref. [25], where both the mathematical derivation and numeric simulations indicate that the error feedback synchronization scheme outperforms the former one when the chaotic signal is transmitted over a noisy channel with an additive white Gaussian noise and a channel filter.

Fig. 4(a) shows the simulation configuration of the error feedback synchronization scheme. In Fig. 4(a), a chaotic Colpitts oscillator is used as a transmitter, and a "copy" of the transmitter with identical parameters is used as a receiver. The chaotic signal generated by the transmitter is sent into a wireless channel, where an additive Gaussian noise and an attenuation are introduced.

In simulations, the circuit parameters are the same as those used in Fig. 2(d), and the initial conditions for the transmitter and receiver are $(10.5, -0.6, 0.01)$ and $(10.8, -0.61, 0.01)$, respectively. The feedback resistance is 50 Ohm. Fig. 4(b) shows the simulation result. We see that although at the beginning, transmitter and receiver oscillate independently, after a period of time (approximately 5 ns here), the chaotic signal in receiver starts to synchronize with that in transmitter. This result shows that the chaos synchronization can be regarded as a signal retrieval process from noise [26–28], which is very suitable for the usage of recovering chaotic RADAR signals from noise and interference.

4. ARCHITECTURE OF THE PROPOSED CHAOTIC RADAR

We have shown that chaotic signals can be ultra-wide band and can be retrieved from noise. Applying the above properties, we can construct a RADAR like that in Fig. 5 where a microwave chaotic oscillator is used as the source for generating RADAR signal. Such signal is isolated and driven by a buffer amplifier and then modulate with carrier, and then be radiated by a transmitter antenna after a power amplifier. If there is a target in air, the backscattered signal (echo) will be received



(a)

(b)

Figure 4. (a) Simulation model for the error feedback chaos synchronization and (b) the corresponding results.

by the receiver antenna, and after going through a low noise amplifier, a demodulator and an adaptive filter, the chaotic signal with noise and delay reaches the chaos synchronization circuit, where, as illustrated in Fig. 4, a delayed copy of the source chaotic signal will be re-generated. After a correlation calculation of the original and recovered chaotic signal by synchronization, the echo signal can be finally detected.

According to above scheme, a system simulation can be run to illustrate how the RADAR works. In simulations, the circuit parameters are the same as those in Fig. 2(d). In Fig. 6, the performance of the system level chaos synchronization is shown also by the Lissajous pattern, in which the horizontal axis represent the V_{C2} signal of the source chaotic Colpitts oscillator while the vertical axis represent the V_{C2} signal in the synchronization module. To show the synchronization performance comparison in a clear way, the time delay between the transmitter and the receiver is omitted. Fig. 6(a) show the perfect synchronization case, corresponding to an infinite large signal-to-noise ratio (SNR). We see that in such case, the Lissajous pattern is just a straight line. When SNR decreases, the Lissajous pattern is expanded. However, we see that even when SNR is $-20\,\mathrm{dB}$, meaning that the noise power is 100 times larger than signal's, we can still distinguish this case from that when SNR is minus infinity in Fig. 6(f), which corresponding to the case of no target. Fig. 7 shows the output of the correlation calculation. Again we see that the echo signal can be distinguished even when SNR is $-20\,\mathrm{dB}$.

Another interesting property of chaotic signals is the "butterfly effect", or the sensitivity to the initial conditions. For two chaotic circuits, even with identical circuit structures and parameters, their output can be irrelevant, or in other words, the signals are orthogonal with each other theoretically, for they can hardly have identical initial conditions. Since circuit parameters, i.e., capacitance, inductance and resistance, can be continuously tuned in wide ranges, the number of orthogonal chaotic signals can be infinite. This means for a correlation receiver, multiple chaotic signals are permitted to co-exist in a same channel. Thus, when there are multiple chaotic RADARs in one area simultaneously, since the chaotic signals generated from different chaotic sources are irrelevant, therefore it could be filtered by the chaos synchronization circuit, and will not influence the basic function of the

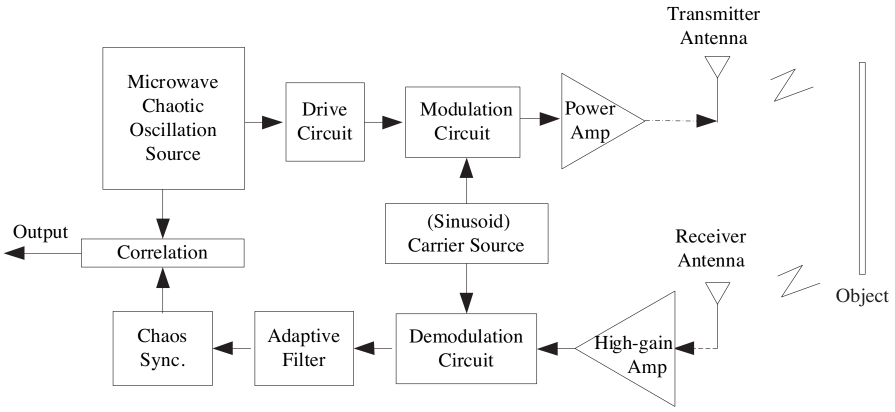
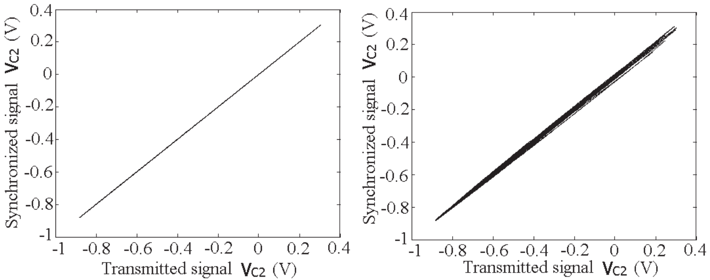
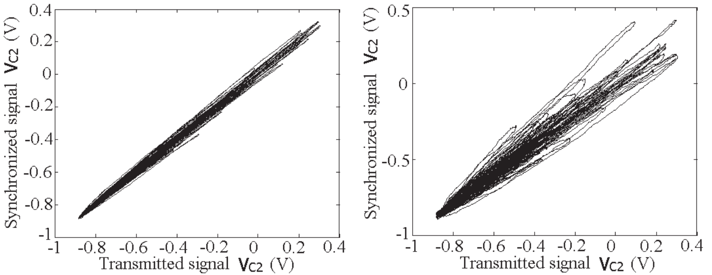


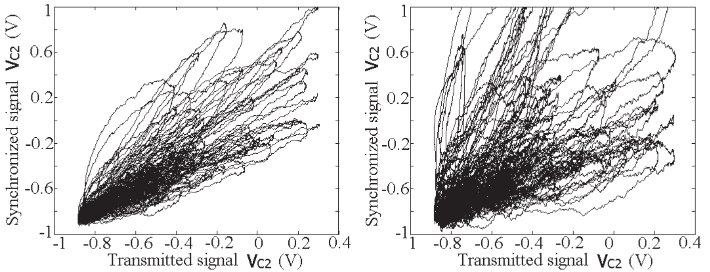
Figure 5. Architecture of the proposed RADAR.



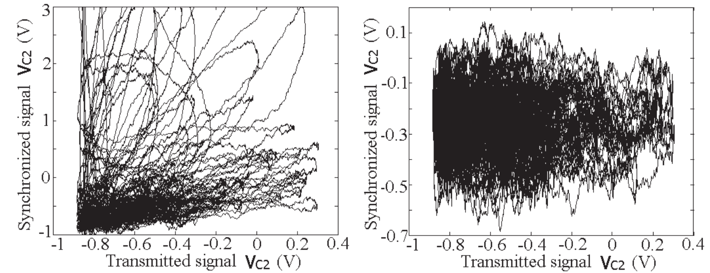
(a): No noise, with detected echos (b): SNR=20dB, with detected echos



(c): SNR=10dB, with detected echos (d): SNR=0dB, with detected echos

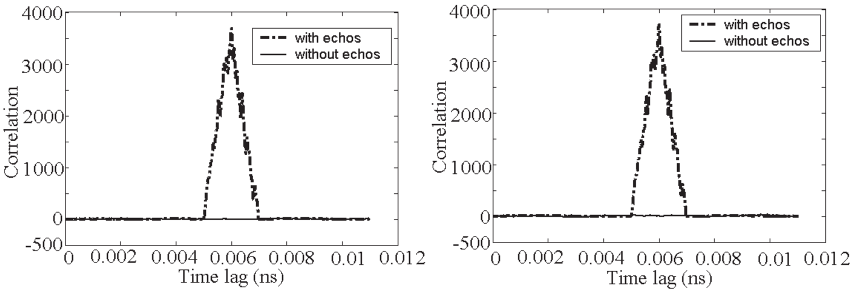


(e): SNR=-10dB, with detected echos (f): SNR=-15dB, with detected echos



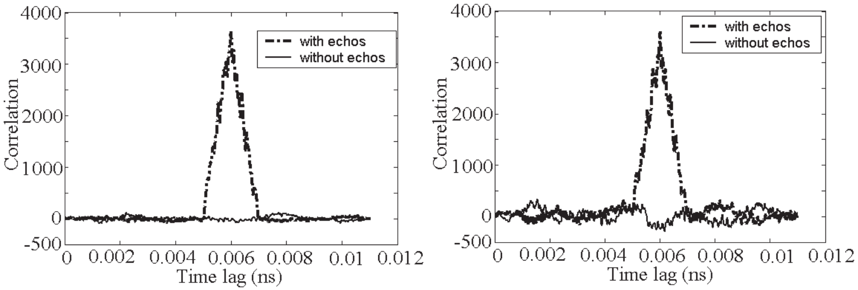
(g): SNR=-20dB, with detected echos (h): Without echos

Figure 6. System simulation of the chaos synchronization in the proposed chaotic RADAR system in a environment existing noise and attenuation. (a) No noise; (b) SNR = 20 dB; (c) SNR = 10 dB; (d) SNR = 0 dB; (e) SNR = −15 dB; (f) SNR = −20 dB; (g) No signal.



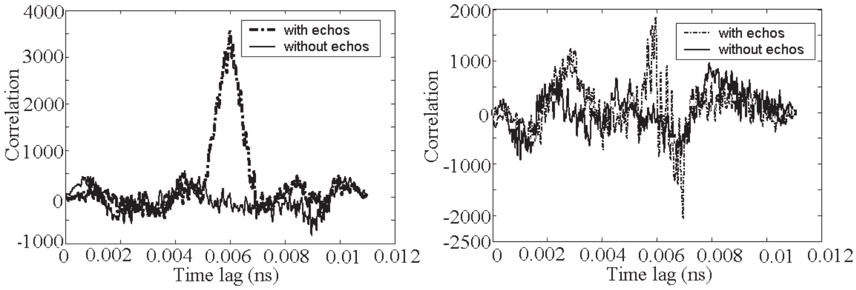
(a): SNR=20dB

(b): SNR=10dB



(c): SNR=0dB

(d): SNR=-10dB



(e): SNR=-15dB

(f): SNR=-20dB

Figure 7. System simulation for the target echo signals in the proposed chaotic RADAR system in a environment existing noise and attenuation. (a) SNR = 20 dB; (b) SNR = 10 dB; (c) SNR = 0 dB; (d) SNR = −15 dB; (e) SNR = −20 dB; (f) No signal.

RADAR. The negative influence of the other chaotic signals is that they raise the noise floor and hence degrade the performance of the RADAR, which is very similar to the spectrum spread communications widely used in CDMA systems.

5. DISCUSSION

In this paper, the possibility of applying microwave chaotic signals and chaos synchronization in constructing a new kind of UWB RADAR is investigated. The system simulations show that such a RADAR system can work under severe interference and with a "multi-user" property like a public wireless communication systems. However, there are also challenges have to be overcome before these advantages can be realized, in which the most difficult one might be the realization of chaos synchronization in microwave band. Fortunately, researches in Ref. [26] have demonstrated the feasibility of the realization of chaos synchronization at very high frequencies.

ACKNOWLEDGMENT

This work was supported by National Key Laboratory Foundation (No. 9140C5304020704), National Natural Science Foundation of China (No. 60671003, No. 60531020), Zhejiang Provincial Natural Science Foundation (No. R105253), China Post Doctoral Science Foundation (No. 20060400313) and partly by Zhejiang Post Doctoral Science Foundation of China (No. 2006-bsh-25).

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