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Anti-control of chaos in p–Ge photoconductor

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We present a scheme for the anti-control of chaos in the p–Ge photoconductor system by using a chaotic laser to irradiate and disturb this system. The numerical simulations show that this scheme can be effectively used to control periodic states in this p–Ge system into chaotic states. Moreover, the different chaos states with different chaotic orbits can be obtained by appropriately adjusting the disturbance intensity and disturbance frequency, and by increasing this intensity or reducing this frequency, this p–Ge system gradually evolves to fully developed chaotic states.

Keywords: anti-control of chaos, p–Ge photoconductor, laser, irradiation
PACC: 0545, 7230, 7240

1. Introduction

Generally, the control of chaos is classified into two sorts, one is suppressing and eliminating chaos when chaos is baneful, the other is generating and strengthening chaos when chaos is useful; the latter is named as the anti-control of chaos. Recently the anti-control of chaos has become an interesting subject of research due to potential applications of chaos phenomena. For example: the existence of chaos in neural networks is helpful to enhance the capability of this system;[1] chaos phenomena can also be applied in secure communication systems.[2] Some relative investigations have been reported. Chen *et al*[3] proposed a feedback control design method for anti-control of chaos in a discrete-time dynamical system. Wang *et al*[4] proved that the method presented in Ref.[3] can lead to chaos not only in the sense of Devaney but also in the sense of Li and Yorke for both linear and nonlinear autonomous systems. For the continuous-time system, Yang *et al*[5] studied the chaos generation by using an impulsive control input. Ren *et al*[6] reported anti-control of chaos via direct time delay feedback, and so on.[7−11] With the rapid development in fabrication technology and extrinsic semiconductor materials, the investigations on extrinsic photoconductors have attracted much attention due to their extensive applications, such as photo-detectors and sensors. Previously, Teitsworth *et al*[12−17] studied nonlinear oscillations and chaos in extrinsic Ge photoconductors experimentally and numerically. Recently, Shiau *et al*[18−21] studied numerically chaotic behaviours in n–GaAs. In addition, Kyritsi *et al*[22,23] reported the chaotic photoconductivity and route into chaos in excited photoconductors. In this paper, we investigate the anti-control of chaos in the p–Ge photoconductor since its chaos states may lead detectors made from this p–Ge photoconductor to disabled, so the chaotic state in the p–Ge system is beneficial when we want to destroy these detectors.

2. Scheme for anti-control of chaos

Here we propose a scheme for the anti-control of chaos in the p–Ge photoconductor by making use of the chaotic laser. On the one hand, the chaotic laser can be produced by using the laser equipment due to its nonlinear dynamical mechanism; on the other hand, based on the principle of cascading nonlinear system, the chaotic laser can be obtained by using the nonlinear modulation system[24] even if its input is the no-chaotic laser. So different kinds of chaotic laser can be obtained by using different nonlinear modulation systems. Here the Lorenz type of chaotic laser is used to irradiate and disturb p–Ge photoconductor, so the generation rate of holes in this p–Ge will be changed. Thus chaotic laser and this p–Ge form a composite system, and its dynamical equations are shown as follows:[25]

$$\begin{aligned}\frac{\mathrm{d}X}{\mathrm{d}\tau} &= -\sigma X + \sigma Y,\\ \frac{\mathrm{d}Y}{\mathrm{d}\tau} &= r_{\mathrm{L}} X - Y - XZ,\\ \frac{\mathrm{d}Z}{\mathrm{d}\tau} &= XY - bZ;\end{aligned} \tag{1}$$

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$$\frac{\mathrm{d}p}{\mathrm{d}t} = \gamma_1(a - a_*) + pk(a - a_*) - pra_*,$$
$$\varepsilon\frac{\mathrm{d}E}{\mathrm{d}t} = J_{\mathrm{ext}} - epv_{\mathrm{d}},$$
$$p = a_* - d,$$
$$J_{\mathrm{ext}} = J_0 + \Delta J\sin(2\pi f_{\mathrm{dr}}t), \quad (2)$$

$$\gamma_1 = c_1X^2\gamma, \quad (3)$$

$$t = \frac{\tau}{c_2\omega_0}, \quad (4)$$

where equation (1) is the dynamical equation of chaotic laser,[26] X, Y, and Z are the normalized lasing field, electric polarization intensity, and population inversion density, respectively; r_{L} denotes the pumping intensity. Equation (2) is the dynamical equation of the p–Ge photoconductor,[13] p is the hole density, γ_1 is the generation rate of holes in this p–Ge being irradiated, a is the total acceptor density, a_* is the time-dependent ionized acceptor density, k and r are the field-dependent impact-ionization rate and recombination rate, respectively. $\varepsilon(\mathrm{d}E/\mathrm{d}t)$ is the displacement current and ε is the dielectric constant, J_{ext} is the external current density and its dc and ac components are J_0 and $\Delta J\sin(2\pi f_{\mathrm{dr}}t)$, respectively; v_{d} is the field-dependent drift velocity, and d is the compensating donor density. Here we assume that the space charge is neutrality. So k, r, and v_{d} are given as follows:[14,27]

$$k = k_0\frac{[(1/2)m_*v_{\mathrm{d}}^2/B]^{1/2}}{1 + (1/2)m_*v_{\mathrm{d}}^2/B} \times \frac{1}{1 + \exp\{[B - (1/2)m_*v_{\mathrm{d}}^2]/k_{\mathrm{B}}T_{\mathrm{h}}\}}, \quad (5)$$

$$r = r_0[(3/2)k_{\mathrm{B}}T/U]^{3/2}, \quad (6)$$

$$v_{\mathrm{d}} = v_{\mathrm{s}}(2/\pi)\tan^{-1}[(\pi/2)\mu E/v_{\mathrm{s}}], \quad (7)$$

where k_0 and r_0 are the impact ionization and recombination coefficients, respectively; B is the impurity ionization energy; v_s, μ, and m_* are the saturated drift velocity, the mobility, and the hole effective mass, respectively; U is the average kinetic energy per hole; m_*, T_{h}, and U are expressed as follows:[14,27]

$$m_* = 0.35m_0, \quad (8)$$

$$(3/2)k_{\mathrm{B}}T_{\mathrm{h}} = (3/2)k_{\mathrm{B}}T + \eta(1/2)m_*v_{\mathrm{d}}^2, \quad (9)$$

$$U = (3/2)k_{\mathrm{B}}T + (\eta + 1)(1/12)m_*v_{\mathrm{d}}^2, \quad (10)$$

where m_0 is the electron mass, the coefficient η models the balance between spreading and displacement in the drifted Maxwellian, here we take $\eta \approx 1.0$.[14,27]

Equations (3) and (4) are used to express the laser irradiation and disturbance of the p–Ge photoconductor, c_1 and c_2 are the disturbance intensity and cycle coefficients, respectively; γ and ω_0 are the original generation rate of holes and character frequency of this p–Ge photoconductor without irradiation, respectively.

In this paper, parameters c_1, c_2 and r_{L} can be taken as the control parameters and can be adjusted by using different laser equipments and different nonlinear modulation systems, so as to obtain the suitable chaotic laser and achieve the anti-control of chaos in the p–Ge photoconductor.

3. Numerical simulations

To illustrate the process of the anti-control of chaos in this scheme, firstly the p–Ge photoconductor system is remained in the periodic state. Secondly numerical simulations are carried out by solving Eqs.(1)–(10) in three cases: case I is to regard the intensity coefficient c_1 as the control parameter; case II is to use the cycle coefficient c_2 as the control parameter; case III is to take the pumping intensity r_{L} as the control parameter. In this work, the differential equations are numerically solved by using a variable time-step fourth-order Runge–Kutta algorithm with total steps $N_{\mathrm{step}} = 1.2 \times 10^5$, and the bifurcation diagrams are plotted by recording the local maxima in the time series.[28]

Firstly, to make the p–Ge system in periodic state, we solved Eqs.(2) and (5)–(10) with the following parameter values $a = 10^{11}/\mathrm{cm}^3$, $d = 3.0 \times 10^{10}/\mathrm{cm}^3$, $r_0 = 1.0 \times 10^{-5}$ cm^3/s, $\gamma = 1.0 \times 10^{-4}$/s, $k_0 = 2.0 \times 10^{-6}$ cm^3/s, $v_{\mathrm{s}} = 1.0 \times 10^7$ cm/s, $\mu = 1.0 \times 10^6$ cm^2/(Vs), $J_0 = 1.3 \times 10^{-7}$ A/cm^2, $\Delta J = 1.0J_0$, $B = 10$ meV, $f_{\mathrm{dr}} = 0.32f_0$, f_0 is the character oscillation frequency of this p–Ge system with these parameter values and at $\Delta J = 0$, here $f_0 \approx 10000$ Hz. These parametric values are chosen according to the requirement of Ref.[12]. Then the 2-period attractor, the corresponding power spectrum and time series are shown in Figs.1(a), 1(b) and 1(c), respectively.

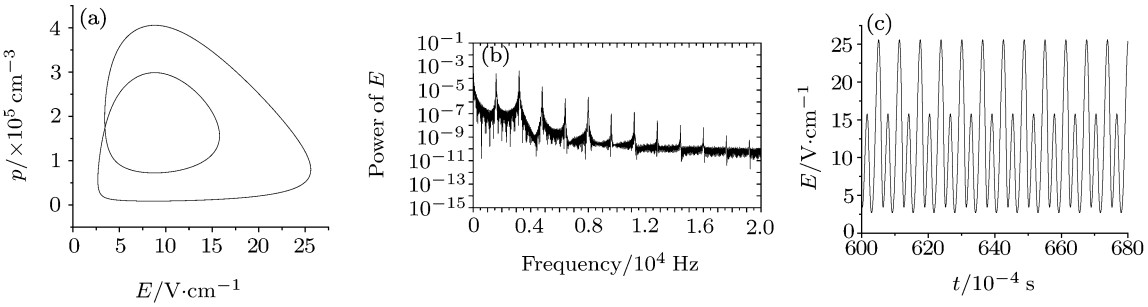
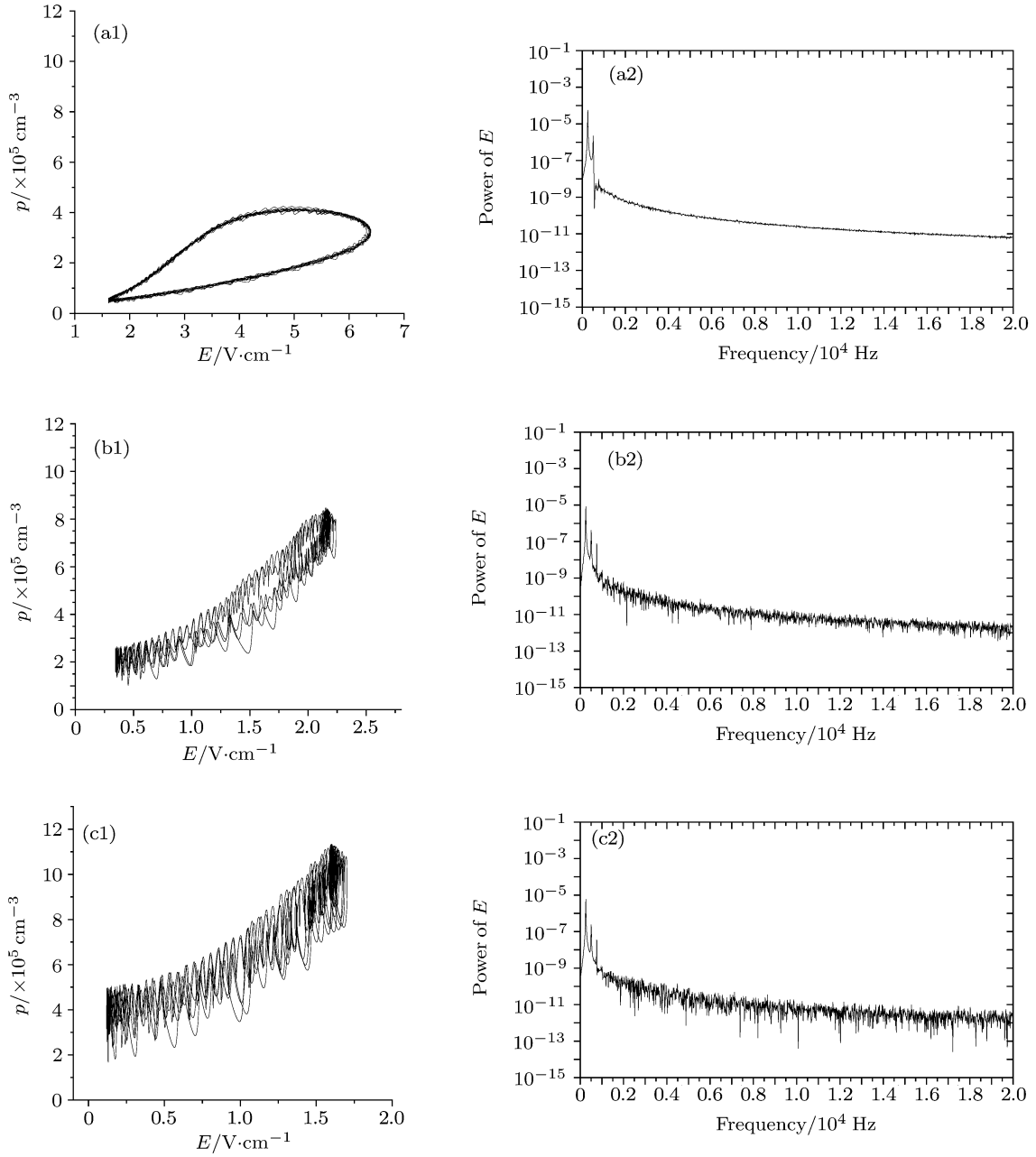


Fig.1. (a) The 2P attractor on plane E–p; (b) the power spectrum, and (c) the time series of E.



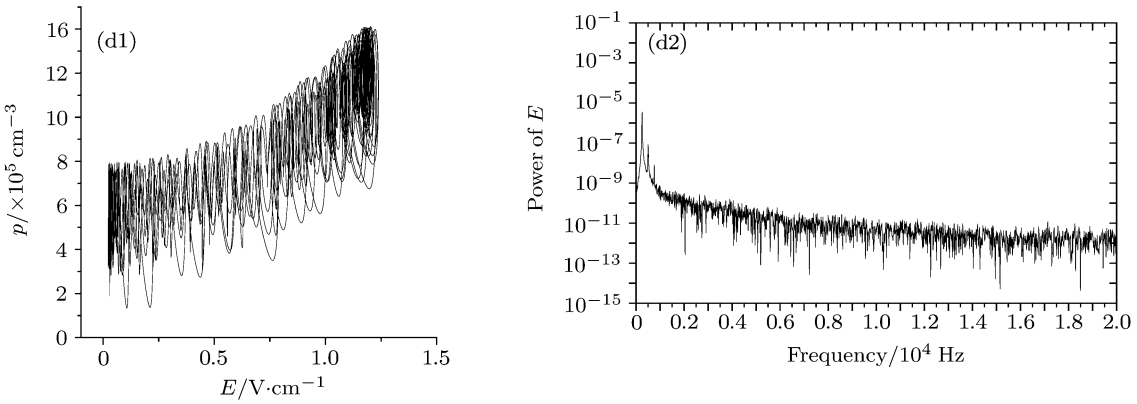


Fig.2. The attractors on plane E–p and power spectrums of E at $c_2 = 2.0$ with different c_1 values: $c_1 = 5.0$ (a1, a2); $c_1 = 50.0$ (b1, b2); $c_1 = 100.0$ (c1, c2); $c_1 = 200.0$ (d1, d2).

Secondly, we study the anti-control of chaos and take $f_0 t$ as the normalized time of the composite system. In cases I, to obtain chaotic laser, we take parameters $\sigma = 16.0$, $r_\mathrm{L} = 46.0$ and $b = 4.0$, with these parametric values at $c_2 = 2.0$, the other parameter values are the same as those in Fig.1, we numerically solved Eqs.(1)–(10). For $c_1 = 5.0$, 50, 100, and 200, the corresponding attractors and power spectrums are presented in Fig.2, where figure 2(a1) shows that the orbits comprise some small thorns because this p–Ge system is irradiated and disturbed by chaotic laser with weak intensity, this attractor is periodic and is period-1 attractor due to $c_2 = 2.0$. Figure 2(a2) shows that no noise spectrum exists and this power spectrum is periodic. So figures 2(a1) and 2(a2) indicate that this p–Ge system is in period-1 state. Figures 2(b1), 2(c1) and 2(d1) show that with increasing c_1, the thorns become bigger and orbits become more jumbled, so these attractors are chaotic. From figures 2(b2), 2(c2) and 2(d2), one can see the noise spectrum, and the noise level increases and noise-band becomes broader with increasing c_1 value. So figures 2(b1)–2(d2) indicate that this p–Ge system is in chaotic states. We have also plotted some other attractors with other c_1 values. The numerical results indicate that this p–Ge system evolves to chaotic state gradually from the original periodic state by increasing c_1 value, for $c_1 \geq 18.0$ this p–Ge system is chaotic, and it can enter to fully developed chaotic state when c_1 value is increased further. Therefore, the periodic state shown in Fig.1(a) can be controlled into chaotic states as shown in Figs.2(b1), 2(c1) and 2(d1) by selecting appropriate c_1 value in the range $c_1 \geq 18.0$ and keeping $c_2 = 2.0$.

In case II we solve Eqs.(1)–(10) by changing the cycle coefficient c_2 within the region $0.1 \leq c_2 \leq 2.0$ and keeping $c_1 = 50.0$, other parameter values are the same as those in Fig.2. The numerical results indicate that this p–Ge system is in chaotic state in the selected parameter region. At several different c_2 values, chaotic attractors and the corresponding power spectrums are presented in Fig.3, where figure 3(c2) shows clearly five peaks, which are near 0.32×10^4 Hz, 0.64×10^4 Hz, 0.96×10^4 Hz, 1.28×10^4 Hz, and 1.60×10^4 Hz, respectively. These frequencies are fundamental and harmonic frequencies of the p–Ge photoconductor irradiated by no-chaotic laser, such as the case of r_L=20.0–31.0 and other parametric values are the same as those in Fig.3. The first one is the fundamental frequency, the others are the harmonic frequencies. From Figs.3(b2) and 3(a2), one can see, respectively, five peaks and three peaks because the noise spectrums in these three power spectrums become broader and stronger with reducing c_2 value, so the corresponding attractors shown in Figs.3(c1), 3(b1), and 3(a1) become more chaotic.

In case III, we solve Eqs.(1)–(10) by changing parameter r_L within the region $30.0 < r_\mathrm{L} \leq 50.0$ and keeping $c_1 = 100.0$, $c_2 = 1.0$, and other parametric values are the same as those in Fig.2. The maximum Laypunov exponent (MLE) of the laser and the bifurcation diagram of the p–Ge system are, respectively, presented in Figs.4(a) and 4(b), where one can see that for $r_\mathrm{L} \geq 32.5$, the MLE is positive and laser is chaotic, and the p–Ge system is also chaotic. Then, when $r_\mathrm{L} = 31.0$ and $r_\mathrm{L} = 36.0$, the corresponding periodic and chaotic attractors are shown in Figs.4(c) and 4(d), respectively. Thus, the p–Ge system can be controlled into chaotic state only irradiated by chaotic laser. Also, we plot some other attractors with other different r_L values, and

find that this p–Ge system gradually evolves to the fully developed chaotic state when r_{L} is increased in the region $32.5 \leq r_{\mathrm{L}} \leq 50.0$ and other parametric values are the same as those in Fig.4(c).

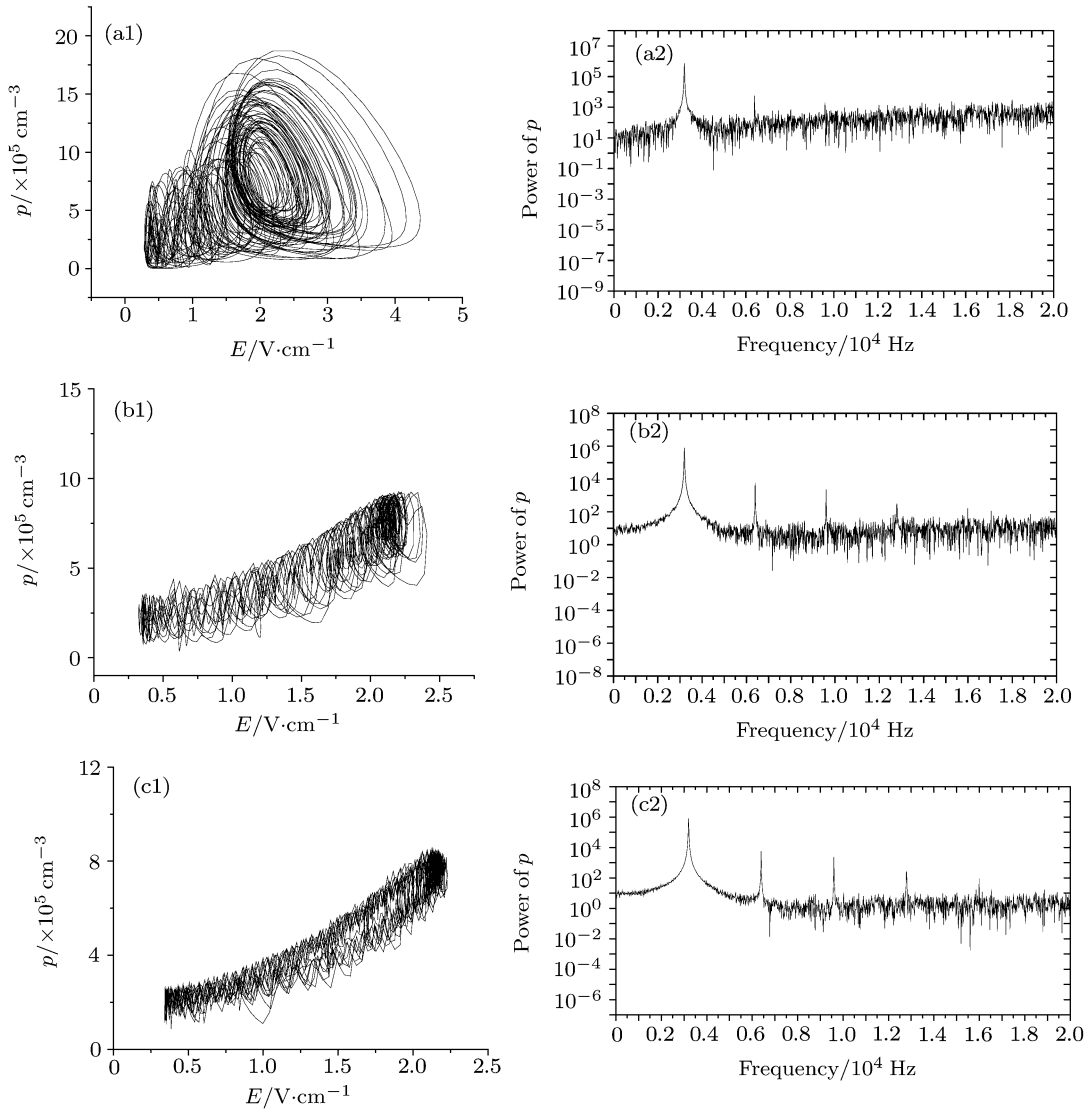
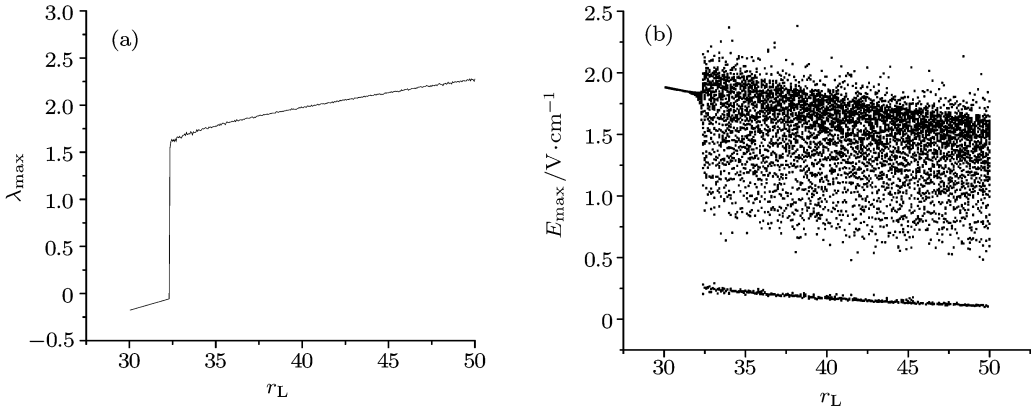


Fig.3. The attractors on plane E–p and power spectrums of p at $c_1 = 50.0$ with different c_2 values: $c_2 = 0.2$ (a1, a2); $c_2 = 0.8$ (b1, b2); $c_2 = 1.8$ (c1, c2).



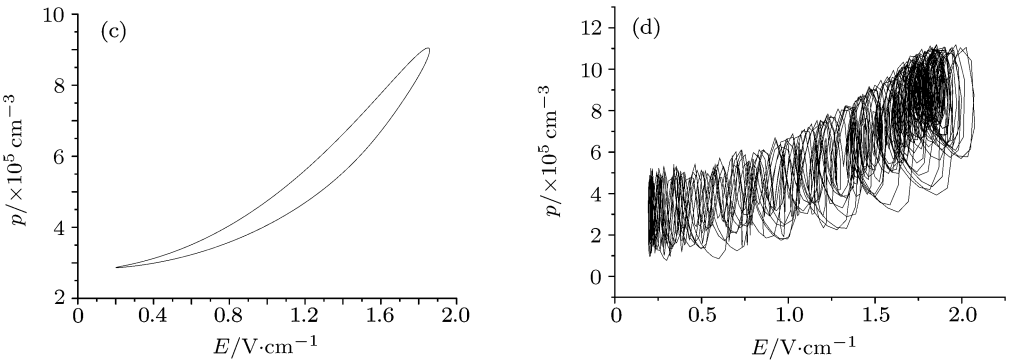


Fig.4. (a) The MLE $\lambda_{\max}$ of laser system via $r_{\rm L}$; (b) The bifurcation diagram of the p–Ge system via $r_{\rm L}$; (c) and (d) The periodic and chaotic attractors on plane E–p with $r_{\rm L} = 31.0$ and $r_{\rm L} = 36.0$, respectively.

In addition, one can see that the orbit in Fig.3(a1) is different from that in Figs.2(b1), 2(c1) and 2(d1). Namely, the different chaotic orbits can be reconstructed by appropriately adjusting the values of parameters c_1, c_2, and $r_{\rm L}$.

Therefore, the periodic state [Fig.1(a)] can be converted into the different chaos states with different chaotic orbits [Figs.2(b1), 2(c1) and 2(d1), Figs.3(a1), 3(b1) and 3(c1), and Fig.4(d)], and we have achieved the anti-control of chaos in the p–Ge photoconductor by using this scheme.

In case I, the chaotic laser is stronger for bigger c_1; In case III, the laser becomes more chaotic and its frequency becomes bigger for bigger $r_{\rm L}$. So, for these two cases, both bigger c_1 and bigger $r_{\rm L}$ may induce the increase of the disturbance to the dynamical state of the p–Ge system, and this system can gradually evolve to the fully developed chaotic state from the original periodic state by increasing c_1 or $r_{\rm L}$ in the selected parameter ranges. In case II, according to Eq.(4), smaller c_2 means that the disturbance frequency is bigger, so the orbits shown in Figs.3(a1), 3(b1) and 3(c1) become more chaotic and the noise spectrums in Figs.3(a2), 3(b2) and 3(c2) become broader and stronger by reducing c_2 value in the region $0.1 \le c_2 \le 2.0$.

4. Conclusion

We have investigated the anti-control of chaos in the p–Ge photoconductor by using the chaotic laser to irradiate it. The numerical results demonstrated that the steady period state in this p–Ge system can be controlled into chaotic states. Moreover, the different chaotic orbits, such as Figs.2(b1), 2(c1) and 2(d1) and Figs.3(a1), 3(b1) and 3(c1), can be reconstructed by appropriately adjusting the intensity coefficient c_1, the frequency coefficient c_2, and the pumping intensity $r_{\rm L}$; and this p–Ge system gradually evolves to the fully developed chaotic state by increasing c_1 and $r_{\rm L}$ values or reducing c_2 value in the selected parameter ranges. For the p–Ge photoconductor, this paper has achieved the anti-control of chaos, i.e., the generation of chaos. This may be useful for applying chaos in destroying detectors made from the p–Ge photoconductor.

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