

# Optical-pulse-injection induced chaos and its control in semiconductor lasers

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We have demonstrated and characterized the generation of various period states in an optical pulse-injected semiconductor laser. We numerically reveal the rich dynamics of chaos and its control in semiconductor lasers based on the optical-pulse injection. The results show that the semiconductor laser exhibits the rich period states by a method of changing the frequency of optical-pulse under different injected parameters, the laser can be controlled into single-periodic, dual-periodic, triple-periodic, four-periodic, multi-periodic and even chaos respectively. The results also provide what we believe to be a new method to generate various period states in the chaos system.

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*Keywords:* Semiconductor laser, Frequency, Optical injection

## 1. Introduction

Chaos and its control in semiconductor lasers have been extensively studied for its potential and unique applications, such as secured communications [1], feedback interferometer[2], all-optical frequency conversion [3], laser chaos-based lidar [4], radar [5]and sensors[6]. During the last decades, many efforts have been done in order to enlarge the modulation bandwidth of laser, where the strongly optical injection locking from another laser has been proven to be one of the valid approaches [7-11]. In particular, in order to increase the signal transmission rate of SLs in chaos communication system, the bandwidth-enhanced unidirectional chaos synchronization between SLs was proposed through using strongly injection-locking technique [10], where both transmitter laser and receiver laser are respectively subjected to external optical injection from different lasers. Very recently, nonlinear dynamics of semiconductor lasers under repetitive optical pulse injection have been investigated numerically.

In this paper, we extend the systematical frame of [13] to the case of semiconductor lasers under repetitive optical pulse injection in chaos communication system. The optical-pulse-injection induced chaos and its control between a master laser (ML) and slave laser (SL) have been investigated numerically in certain conditions. when the modulation frequencies of optical-pulse and the

coupling coefficients are changed synchronously, the slave laser (SL) show the rich dynamics, such as single-periodic, dual-periodic, triple-periodic, four-periodic, multi-periodic and chaos.

## 2. Model

The systematical configuration is depicted in Fig. 1. The chaotic laser system consists of a master laser (ML), optical isolator, optical controller and a slave laser (SL). The light output ( $E_m$ ) of SL experiences the optical isolator, optical controller and modulates ML.

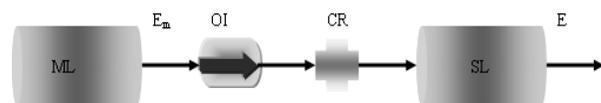


Fig. 1. System configuration in an optically injected SL

ISO: Optical isolators; OCR: Optical controller.

Our present study is based on an extended a set of following modified rate equations including the laser fields  $E$ , the phases  $\varphi$ , and the carrier number  $N$  in active region. This system can be theoretically described by [8-12]:

$$\frac{dE}{dt} = \frac{1}{2}(G - \nu_p)E + \frac{k \cdot E_m F}{\tau} \cos(-\varphi) \quad (1)$$

$$\frac{d\varphi}{dt} = \frac{1}{2}\beta_c(G - \nu_p) + \frac{k}{\tau_l} \frac{E_m F}{E} \sin(-\varphi) - \Delta\omega_m \quad (2)$$

$$\frac{dN}{dt} = \frac{I}{q} - \nu_e N - GV_p E^2 \quad (3)$$

where  $E$  and  $\varphi$  are the slowly varying electric field and phase of the laser optical field, respectively.  $N$  is the carrier number in the laser cavity.  $G (= (V\nu_g\alpha/V)(N-N_{th})/\sqrt{1+E^2/E_s^2})$  is the mode gain,  $\nu_g$  is laser cavity photon group velocity,  $\alpha$  is the gain constant ( $=V/V_p$ ) is the compression and confinement factor,  $V$  is the volume of laser cavity,  $V_p$  is the volume of laser mode,  $E_s$  is the saturation photon field-strength.  $N_{th}=n_{th}V$  is the carrier number at transparency,  $n_{th}$  is the carrier density at transparency.  $\nu_p = \nu_g(\alpha_m + \alpha_{int})$  is the cavity decay rate of photon,  $\alpha_m$  is the external photon decay of cavity,  $\alpha_{int}$  is the internal photon decay of cavity.  $\Delta\omega_m$  is the detuning of the angular frequency between the master and slave lasers.  $\tau_l = 2n_g L/c$  is the optical round-trip time in the laser cavity length of  $L$ ,  $c$  is the vacuum speed of light,  $n_g = c/\nu_g$  is the group velocity refractive index.  $I$  is the drive current,  $q$  is the electronic charge.  $\beta_c$  is linewidth enhancement factor.  $\nu_e = A_{nr} + B(N/V) + C(N/V)^2$  is non-linear decay rate of carrier,  $A_{nr}$  is non-radiative recombination rate,  $B$  is the radiative recombination factor,  $C$  is the auger recombination factor.  $k$  is optical injection coefficient. The parameter  $F (= \sin(2ft))$  in Eq. (1)-(2) represents the effect of Optical-pulse-injection on SL. The parameter  $f$ , the term governing modulation frequency.

### 3. Results and discussion

The rate equations (1)-(3) can be numerically solved by fourth-order Runge-Kutta method. The other parameters values used in the calculation are chosen as [9-15]:  $L=350\mu\text{m}$ ,  $w=2\mu\text{m}$ ,  $d=0.15\mu\text{m}$ ,  $\Gamma=0.29$ ,  $n_g=3.8$ ,  $\alpha_m=29\text{cm}^{-1}$ ,  $\alpha_{int}=20\text{cm}^{-1}$ ,  $\Delta\omega_m=2\pi\times 10^9\text{rad/s}$ ,  $\beta_c=6$ ,  $E_m=0.126E_s$ ,  $n_{th}=1.2\times 10^{18}\text{m}^{-3}$ ,  $A_{nr}=1\times 10^{18}\text{s}^{-1}$ ,  $B=1.2\times 10^{-10}\text{cm}^3\text{s}^{-1}$ ,  $C=3.5\times 10^{-29}\text{cm}^6\text{s}^{-1}$ ,  $I=25\text{mA}$ ,  $E_s=1.6619\times 10^{11}\text{m}^{-3/2}$ ,  $\alpha=2.3\times 10^{-16}\text{cm}^2$ . To demonstrate the characterization of optical-pulse-injection induced chaos and its control in semiconductor lasers, the time series and phase diagram in the semiconductor laser with direct injection are shown in Figure 2. It can be clear that, when the semiconductor laser is modulated directly, the output

dynamics is chaotic from the time series and phase diagram for a given coupling constant ( $k=0.05e-3$ ); Figure 3 (a)-(d) represents the time series and phase diagram with different frequencies for various values of the coupling constant. When the modulation frequency  $f$  is  $1.191\text{GHz}$ , the SL is controlled to single-cycle from the time series and phase diagram. As the increase of  $f$ , the time series show a single peak structure, the phase diagram remains unchanged, which shows a steady state(one-cycle) at  $f (=1.51\text{GHz})$ ; For  $f (=3.212\text{GHz})$ , the time series and phase diagram both show a single-periodic state. In addition, the pulse power gradually decreases with the increase of the injected signal's frequency.

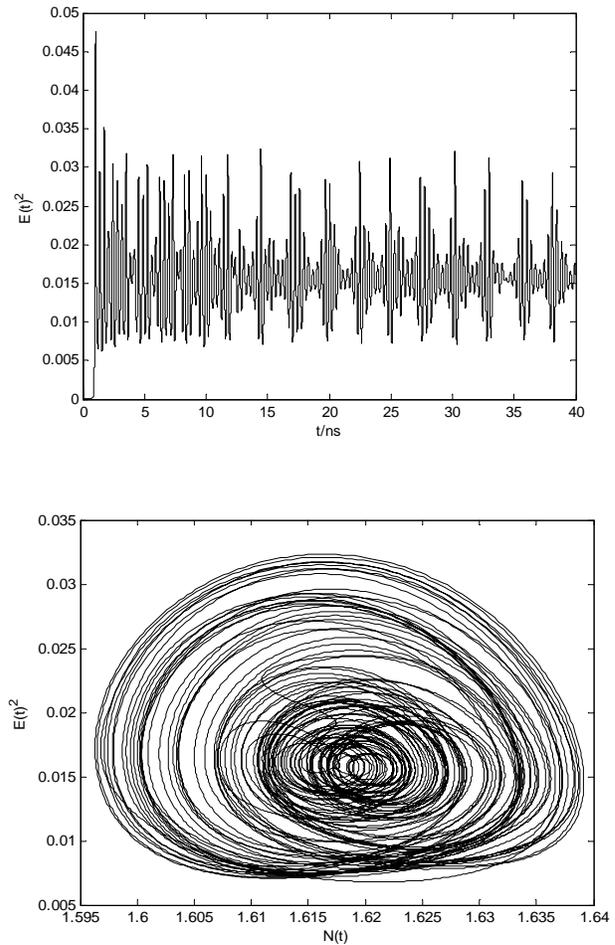


Fig. 2 Time series and phase diagram in SL with direct injection.

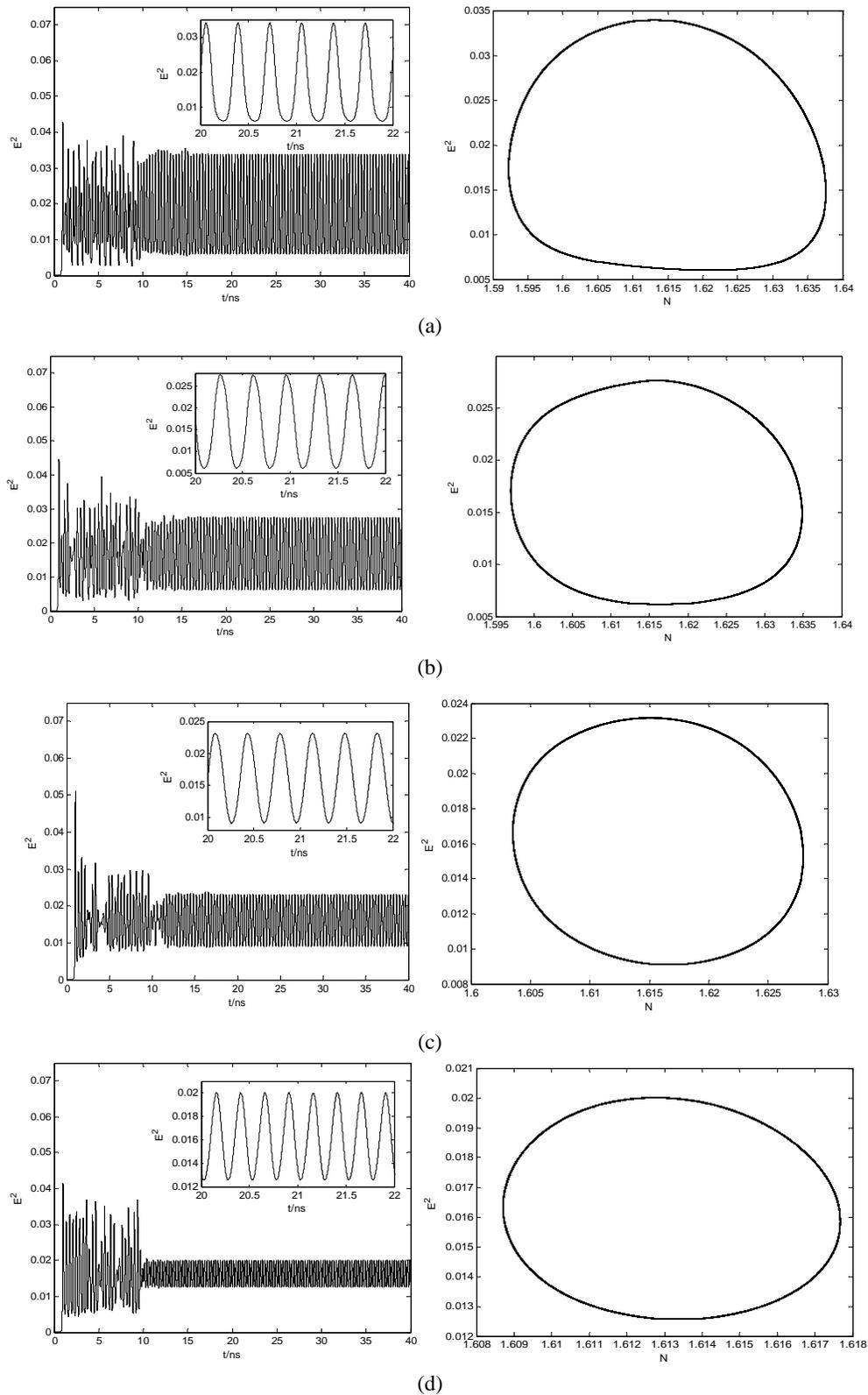


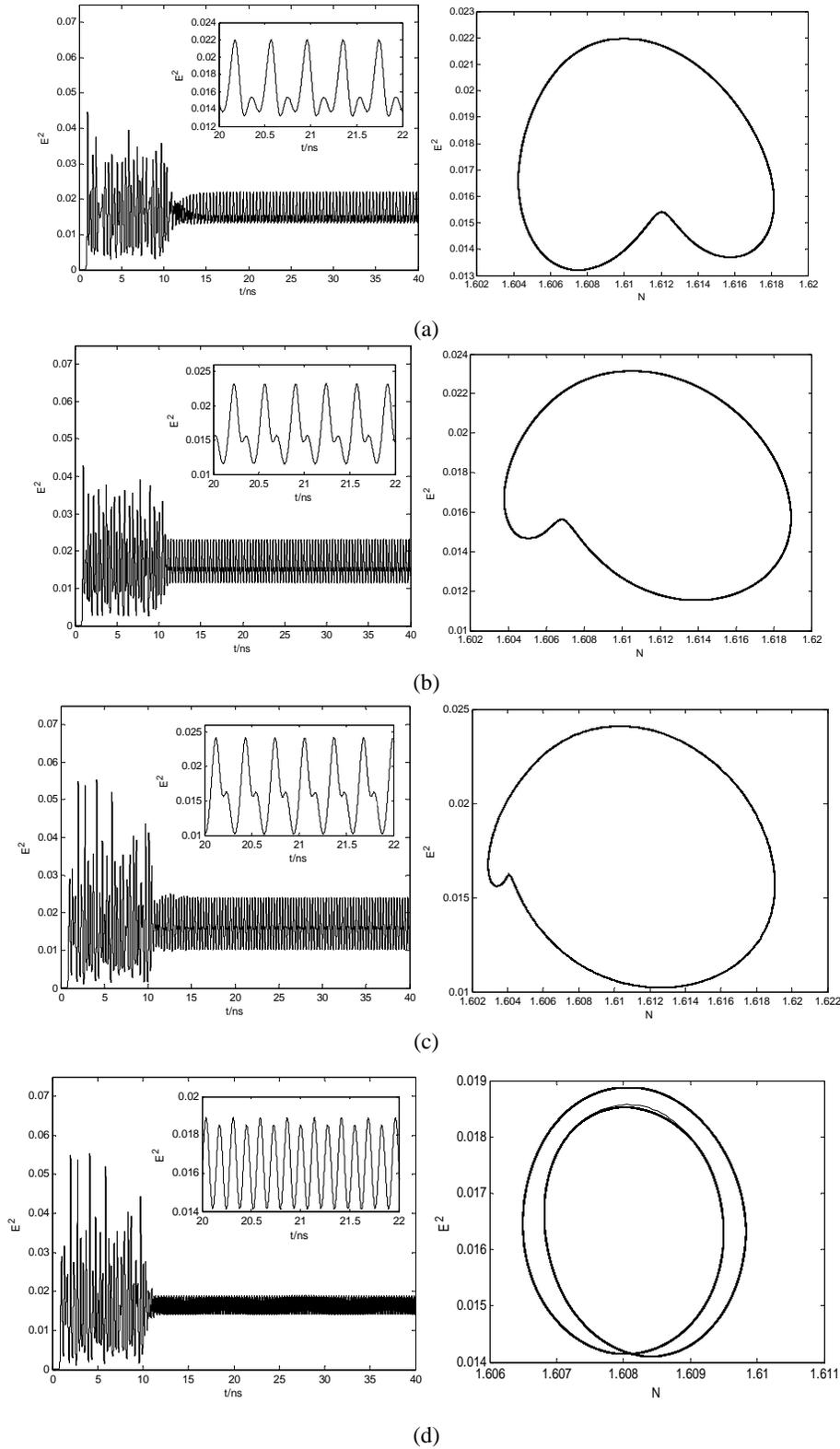
Fig. 3. Time series and phase diagram in SL with the different frequencies for a given injected parameter.

Under appropriate conditions, the system can produce dual-periodic states at different modulation frequencies by changing the optical injection coefficient. Here, we select

different injection coefficients and modulation frequencies, the system can produce several kinds of two-cycle state. when  $k$  is 0.0356, the phase portrait and the time series show two-cycle

state for  $f=2.55$  GHz). With the increase of ( $k=0.424$ ), the orbit changes apparently at  $f=2.96$  GHz). As  $k(=0.05, 0.065, 0.0264)$  is further increased, the time series and phase diagram still show two-cycle state for  $f=3.2$  and  $3.65$  GHz), even for  $f=1.35$  GHz. The results show that, every dual-period states can

be controlled much easier, the system can be adjusted and controlled in a large parameter range, its oscillation frequency is very close to the corresponding modulation frequency.



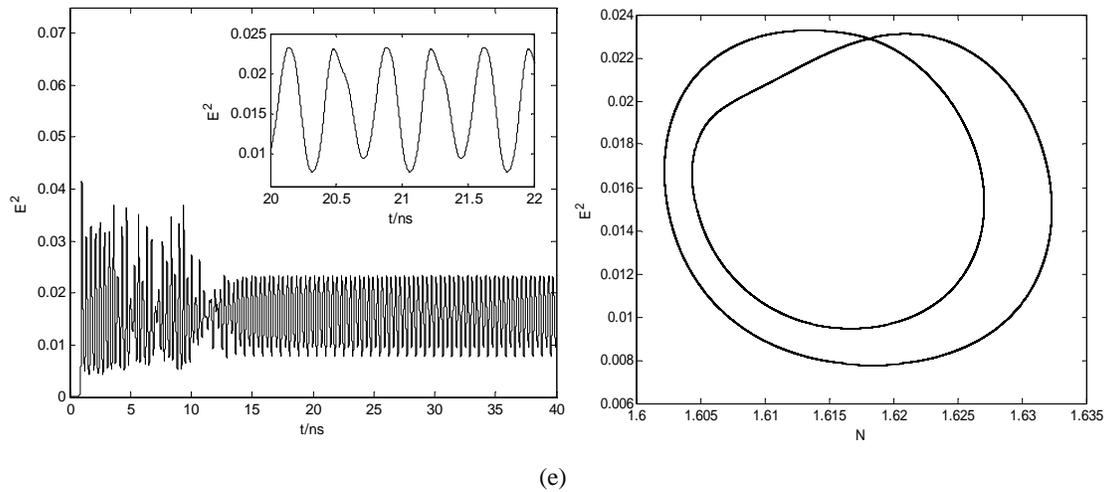


Fig. 4. Time series and phase diagram in SL with the different frequencies for a given injected parameter

In order to achieve more cycle states, the parameters of SL are very important. Therefore, it is necessary to investigate the effects of parameter on chaos and its control in this scheme; we concentrate on the dynamics for the different  $k$  and  $f$ , the term governing modulation frequency. Figure 5 shows the time series and phase diagram of the output dynamics versus  $k$  at different modulation frequency in ML. As  $k$  is 0.09, the system is suppressed three-cycle at  $f(=4.477\text{GHz})$ ; when  $k$  is decreased, the SL takes on another three-period state with the increase of  $f$ , the orbit of the phase diagram changes obviously; As  $k$  is decreased further, the time series and phase diagram still show three-period for  $k=0.05$  and  $f=6.17\text{GHz}$ .

Here, we select another group of  $k(=0.07)$  and  $f(=4.43\text{GHz})$ , the three-cycle controlled in the system are shown as Figure 5(d). Besides, the pulse power gradually decreases with the increase of the injected signal's frequency. Compared with the previous results, Figure 6(a)-(c) presents time series, phase correlation diagram of the output of SLs for the different coupling constant  $k$  at difference modulation frequency  $f$ . From these diagrams, the phase portrait shows four-cycle state, when the values of coupling constant  $k(=0.0103, 0.0198, 0.09)$  are taken and the corresponding modulation frequency  $f(=2.0133\text{GHz}, 2.012\text{GHz}, 4.765\text{GHz})$ , respectively. And the pulse power changes apparently. The results indicated that, the system based on optical-pulse-injection easily realizes all types of the three-cycle or four-cycle state by using the different coupling constant  $k$  at difference modulation frequency  $f$ . In addition, the system has a larger space of parameters.

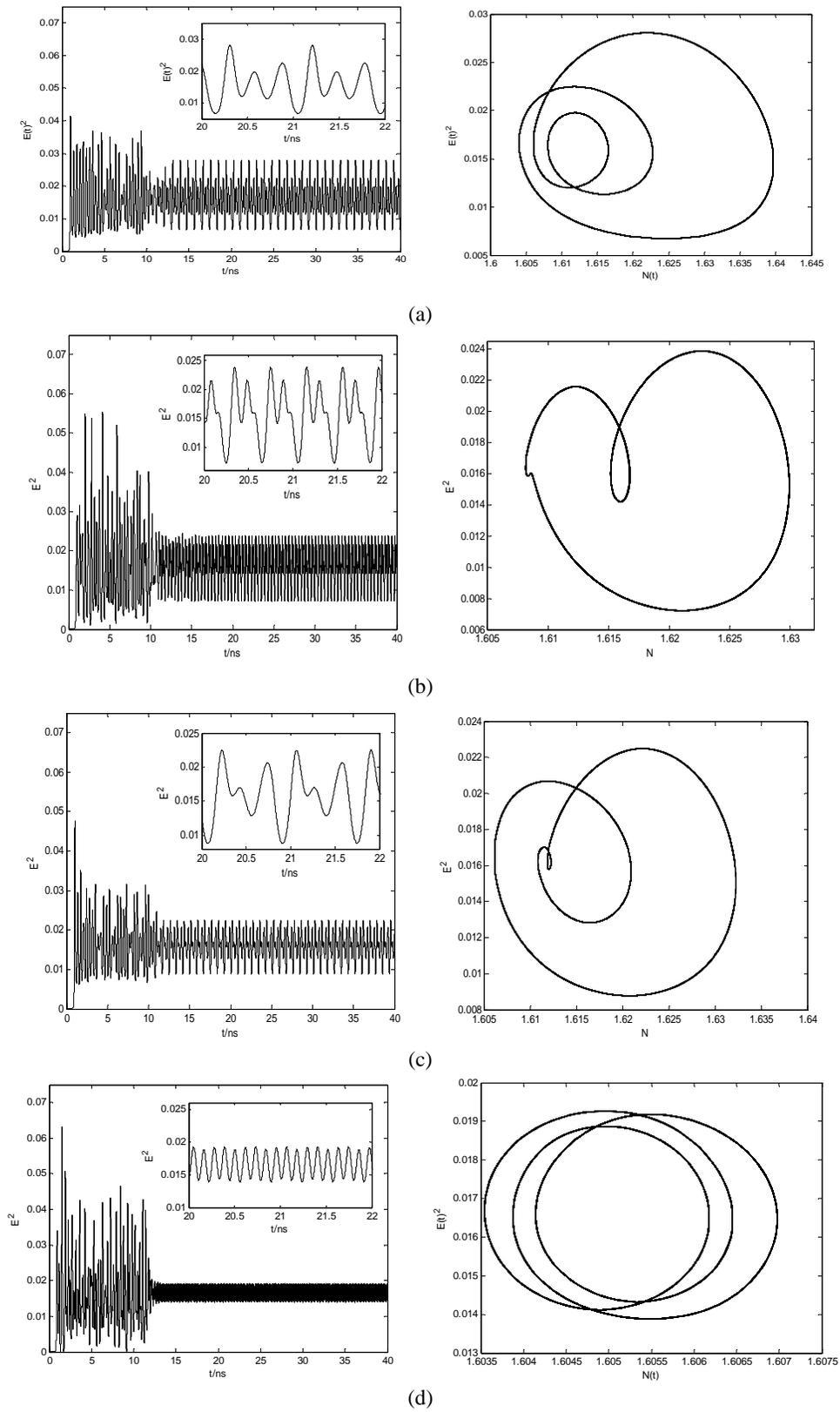


Fig.5 Time series and phase diagram in SL with the different frequencies for a given injected parameter

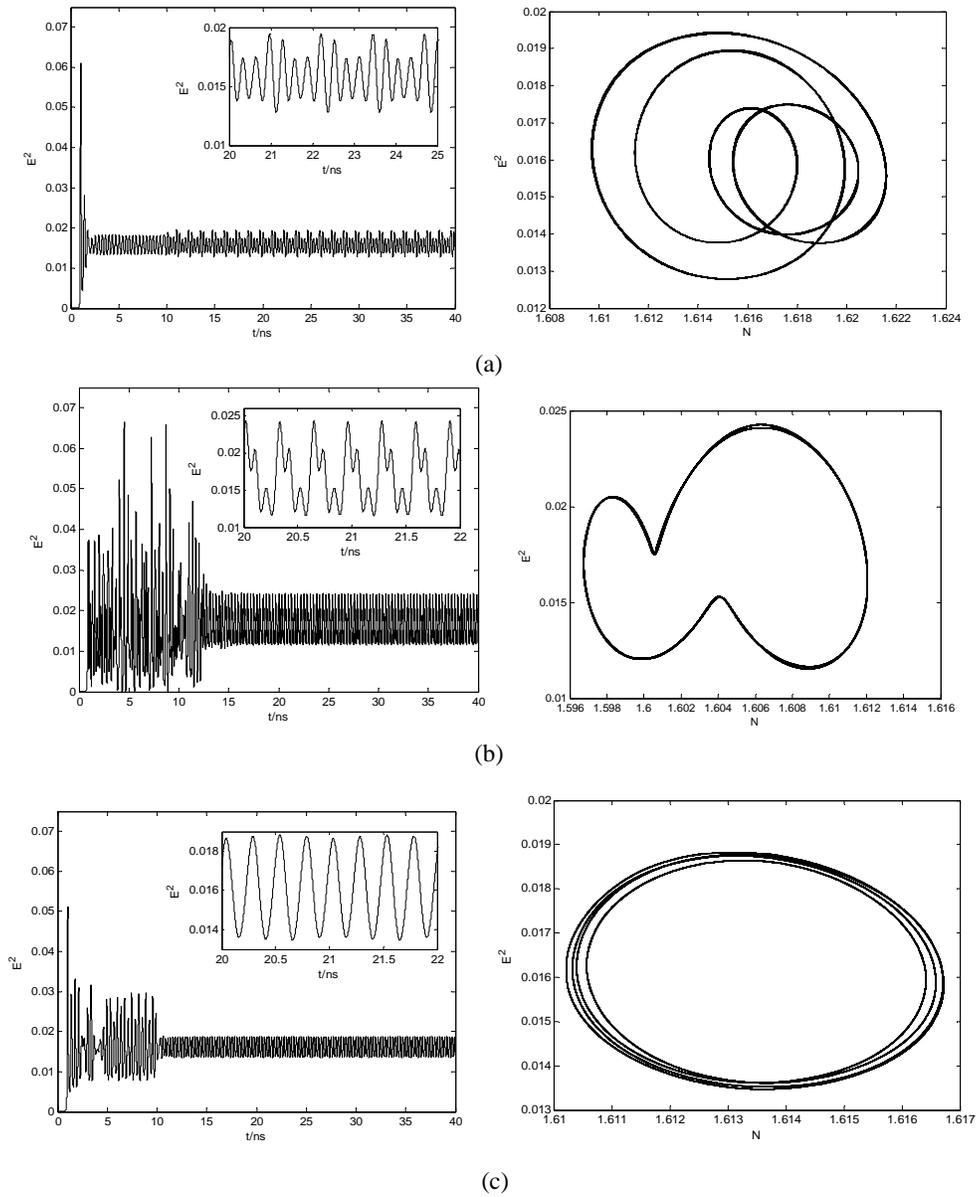


Fig.6 Time series and phase diagram in SL with the different frequencies for a given injected parameter.

In Figure 7(a), as the coupling strengths and modulation frequency are increased further, the time series diagram shows the multi-peak power, and the system is controlled multi-period state from the phase diagram, namely the system remains the multi-periodic state. When the optical injection coefficient and the modulation frequency are 0.09 and 4.48GHz, the system is controlled to multi-periodic; compared with the previous results in Figure 7(a), the chaos in the time series and phase diagram is shown as Figure 7(b).

These results show that there are different ranges of coupling strengths and modulation frequency, which can provide us with different dynamical behaviors. Therefore, by choosing appropriate coupling and modulation frequency values, we can use the method of optical pulse-injected for achieving chaos and suppression of chaos.

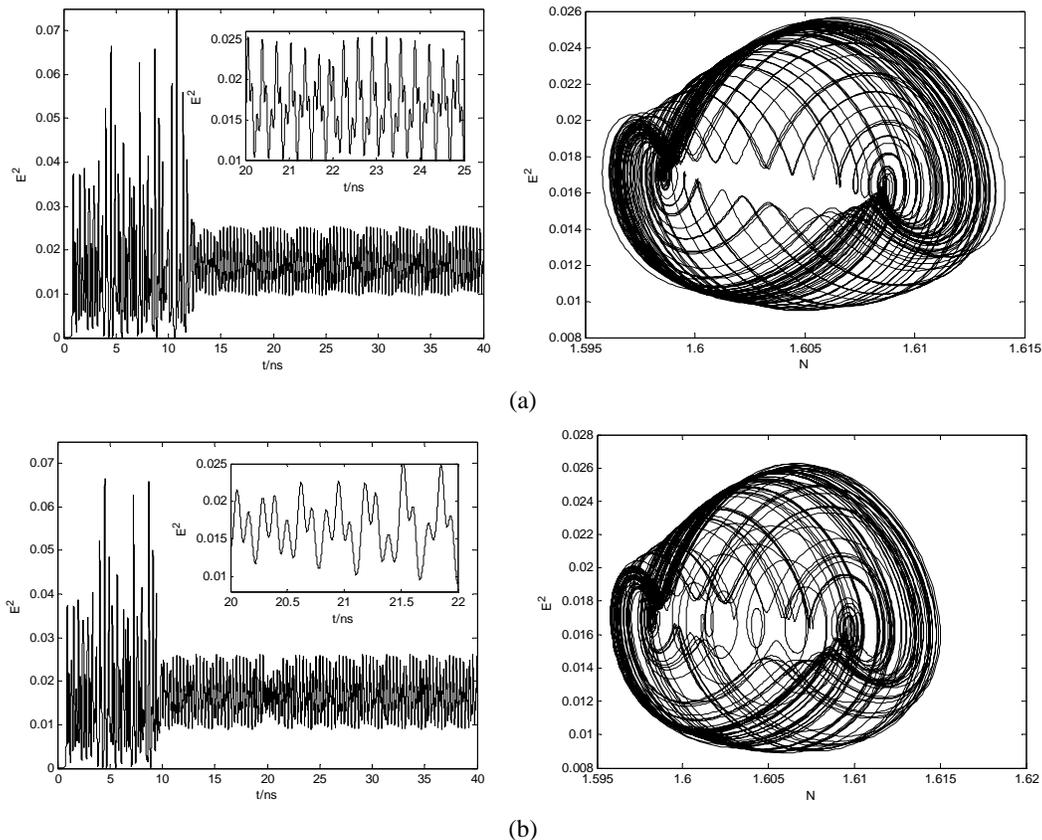


Fig.7 Time series and phase diagram in SL for  $k=0.09$  and  $f=4.58\text{GHz}, 4.4785\text{GHz}$ .

#### 4. Conclusions

In conclusion, we present a physical method to realize and achieve chaos and its control in the semiconductor laser based on optical-pulse-injection. The results show that, chaos can be suppressed and controlled easily, which can effectively control the system from one-cycle state to multi-cycle states, even chaos. Our investigation reveals that the coupling constant and frequency of the injected light of SL play an important role during the process of chaos and its control. This is very helpful to the further study about chaotic control. We hope this work would offer a useful insight to the nonlinear dynamics of SL system.

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