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Study of chaotic characteristics in the semiconductor laser with periodic optical injection

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A periodic control method by external optical injection strength in the semiconductor laser is presented. The numerical simulation results show that when the injection strength is periodic controlled at the time of 10ns, chaotic state will be controlled into periodic state at the appropriate optical injection coefficient, such as single-periodic state, dual-periodic state and three-periodic state et al.. With the optical injection coefficient increases, the modulation frequency will increase. The method can control the chaos to less periodic and more stable state, it's meaningful to improve the efficiency of the laser output and inhibit the generation of chaos.

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Keywords: Semiconductor laser, Chaos, Optical injection, Periodic control

1. Introduction

Chaos is a nonlinear system which is unique and widely exists in the form of a non-periodic motion. The nonlinear system widely exists in physics, chemistry, meteorology, biology and other fields. Under certain conditions, the nonlinear system will output chaos. Chaos has the superiority in some areas, such as the use of noise-like character of chaos' in laser ranging [1] and chaotic secure communication [2]. But in many occasions, chaos has a serious impact on normal production. So at the beginning of chaos theory, when people are concerning about how to use chaos, some people are also exploring how to effectively control chaos.

Since the OGY(Ott-Geobogi-Yorke) method of chaos control was presented by Ott et al.[3] , chaos control methods were rapidly developed, such as continuous variable feedback method[4], adaptive control method[5], parametric resonance method[6], artificial intelligence method[7] et al. have also been successively proposed. In literature [8], chaos is controlled to single-periodic state and dual-periodic state by using fuzzy adaptive sliding mode control method. In literature [9], the numerical simulation results show that by high-frequency injection in a chaotic laser diode, chaos could be controlled to single-periodic state and three-periodic state. In literature [10], the numerical simulation results show that by phase periodic control, laser's chaotic state is controlled to a variety of cycle states. In literature [11], Zou pointed out that by changing the external parameters such as strength, phase et al., chaos could be well controlled. In this paper, the method of external optical injection strength periodic control is presented, the numerical simulation results show that system can be transformed from chaos to multiple-cycle state with appropriate optical injection coefficient and modulation frequency.

2. Theoretical model

At the condition of external optical injection, the system consists of the same master, slave-distributed feedback semiconductor laser [10] as show in Fig.1. In order to effectively control the system from chaotic state to periodic state, a method is presented to control the system as show in Fig.2. In the configuration shown in Fig.2, an amplitude modulator (AM) is placed between the master laser and the slave laser. It includes the external oscillator. It can be used as a strength controller to adjust or shift optical injection strength to slave laser. In this case, chaos control will be realized with the aid of AM.

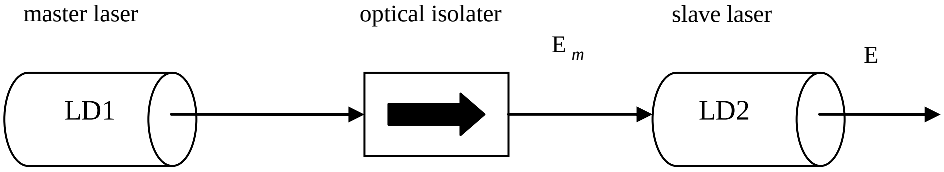

Fig.1. The figure of the external optical injection model

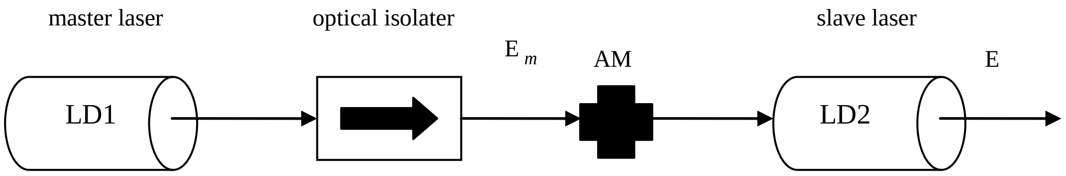

Fig.2. The figure of the chaos-control model

We can use the Lang-Kobayashi equations to describe the dynamics of slave laser when there is external optical injection [11, 12, 13, 14]:

$$\frac{dE}{dt} = \frac{1}{2}(G - v_p)E + \frac{k}{\tau_l}E_m F\cos(-\phi) \tag{1}$$

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

$$\frac{dN}{dt} = \frac{I}{q} - v_e N - GV_p E^2 \tag{3}$$

Where E and ϕ are the laser optical field amplitude and phase, N is the carrier number in the laser cavity. F is the amplitude modulator factor, it is a sine curve, acting on the injection optical field amplitude E_m, which is used to transform the laser output from chaotic to periodic state. $G = (\Gamma v_g \alpha / V)(N - N_{th})/\sqrt{1 + E^2/E^2{}_s}$ is the mode gain, v_g is the laser cavity photon group velocity, α is the gain constant, $\Gamma = V/V_p$ 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. $v_p = v_g(\alpha_m + \alpha_{\text{int}})$ is the cavity decay rate of photon, α_m is the cavity loss, α_{int} is the internal loss. $\Delta\omega_m$ is the frequency detuning between the master laser and the slave laser. $\tau_l = 2n_g L/c$ is the optical round-trip time in the laser cavity length of L, c is the vacuum speed of light, $n_g = c/v_g$ is the group velocity refractive index. I is the drive current, q is the electronic charge. β_c is the linewidth enhancement factor. $v_e = A_{nr} + B(N/V) + C(N/V)^2$ is the non-linear decay rate of carrier, A_{nr} is the non-radiative recombination rate, B is the radiative recombination factor, C is the auger recombination factor. k is the optical injection coefficient. The parameter values used in the numerical simulation is shown in Table 1.

The external oscillator is used to control the amplitude modulator factor F, so designing an external oscillator is a feasible method to periodic control the injection strength. The output signal E_m of the master laser multiplied with the amplitude modulator factor F, the result is a injection signal to the slave laser. F is a sine curve, $F = \sin(2\pi f t)$. At the appropriate optical injection coefficient, by selecting different modulation frequency f, the system can output a wealth of multi-periodic state.

Table 1. The parameter values used in the numerical simulation

parameter	value	parameter	value
L	350um	A_{nr}	1.0×10^{18}s^{-1}
W	2 u$_m$	B	1.2×10^{-10}cm^3/s
d	0.15um	C	3.5×10^{-29}cm^6/s
Γ	0.29	E_s	1.6619×10^{11}m$^{-3/2}$
n_g	3.8	α	2.3×10^{-16}cm^2
α_m	29cm^{-1}	β_c	6
α_{int}	20cm^{-1}	$\Delta\omega_m$	$2\pi \times 10^9$rad/s
n_{th}	1.2×10^{18}cm^{-3}	E_m	0.126E$_s$
I	25mA		

3. Results and discussion

At a certain optical injection coefficient, the laser exports chaotic signal. The numerical simulation results show that when laser injection strength is periodic controlled at 10ns, by selecting the appropriate modulation frequency f, the system can be controlled from chaotic state to multi-cycle state. By changing the optical injection coefficient, selecting the appropriate modulation frequency, system can output different periodic state at different modulation frequency.

First, select the optical injection coefficient k (k=0.0216). Fig. 3, Fig. 4 and Fig. 5 show when the modulation frequency is 1.51GHz, 3.21201GHz and 1.191GHz, the system is separately controlled to single-periodic state, dual-periodic state and three-periodic state. Figure (a) is the time diagram, figure (b) is the spectrum of the laser optical field amplitude and Figure (c) is the phase space attractor. All the diagrams have the same definition except Fig.6. The Fig.6 (a) is the amplification of Fig.3 (a). In order to confirm the controlled state is a periodic state, we calculate the period in Fig.6 (a). We take a cycle form 19.36ns to 19.69ns, so the period is 0.33ns, the frequency is 3.0303×10^9Hz. The frequency in Fig.6 (b) is 3.0×10^9Hz, so we can confirm the controlled state is a periodic state and the other diagram's period can be also calculated by this way.

As can be seen from Fig.3, Fig.4 and Fig.5, regardless of the system initially in a chaotic state, when it is controlled to a periodic state, there is a certain relaxation time, the longest relaxation time is no more than 15ns. Its oscillation frequency is very close to the corresponding modulation frequency.

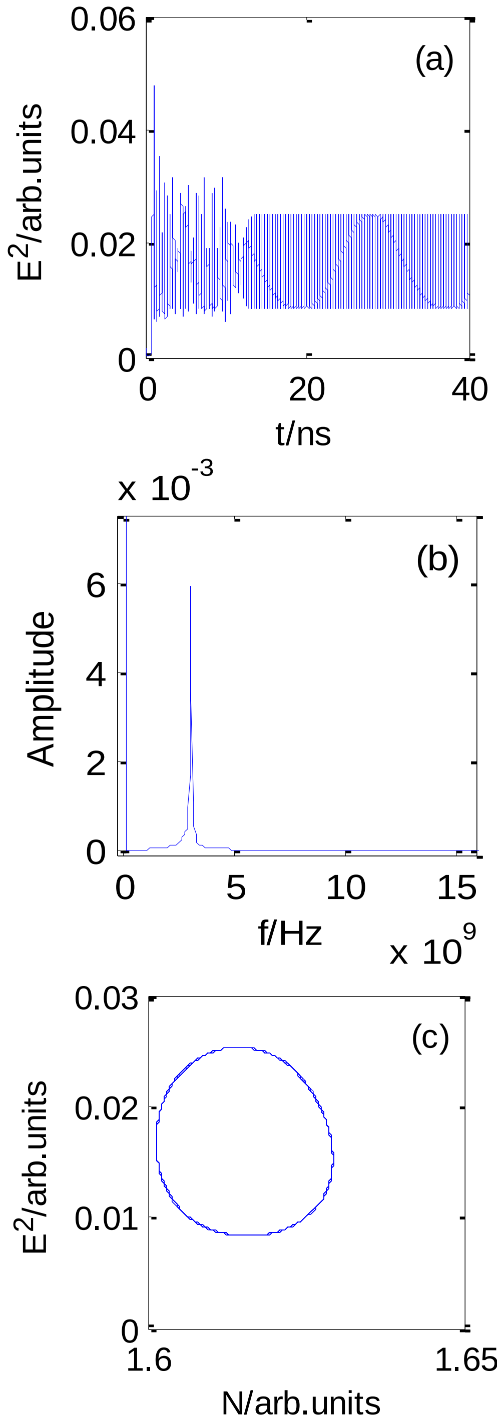

Fig.3. k=0.0216, f=1.51GHz, system is kept to a single-periodic state.

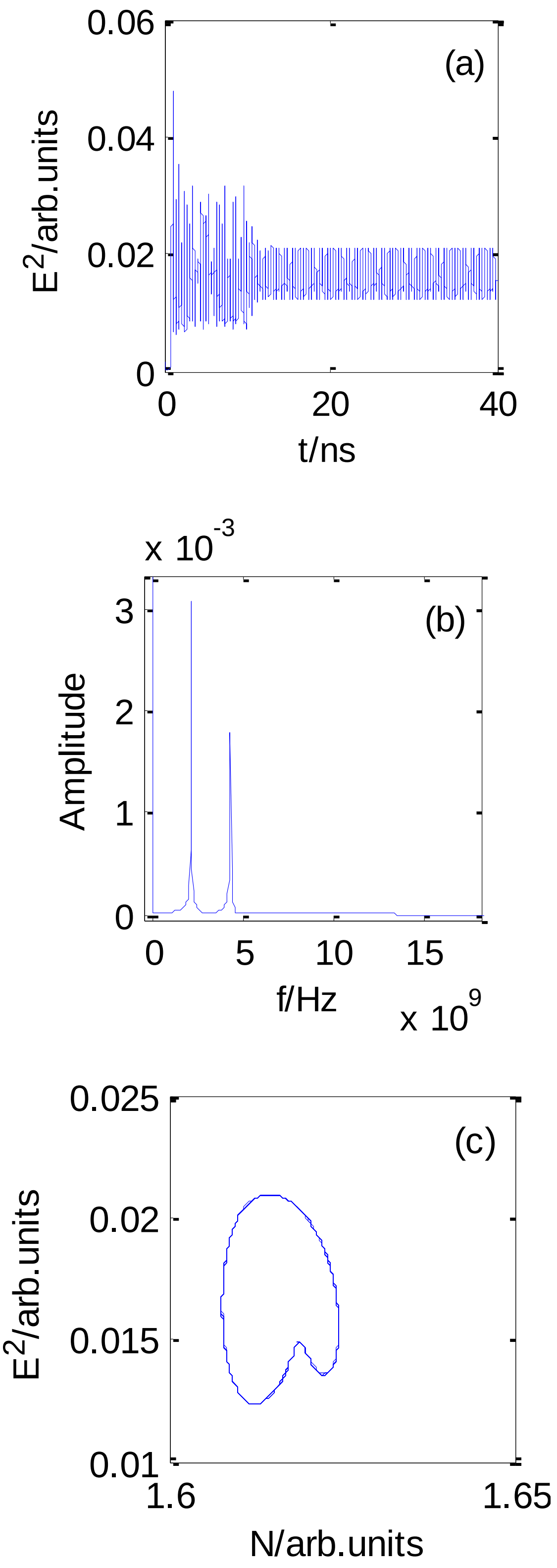

Fig.4. k=0.0216, f=3.21201GHz, system is kept to a dual-periodic state

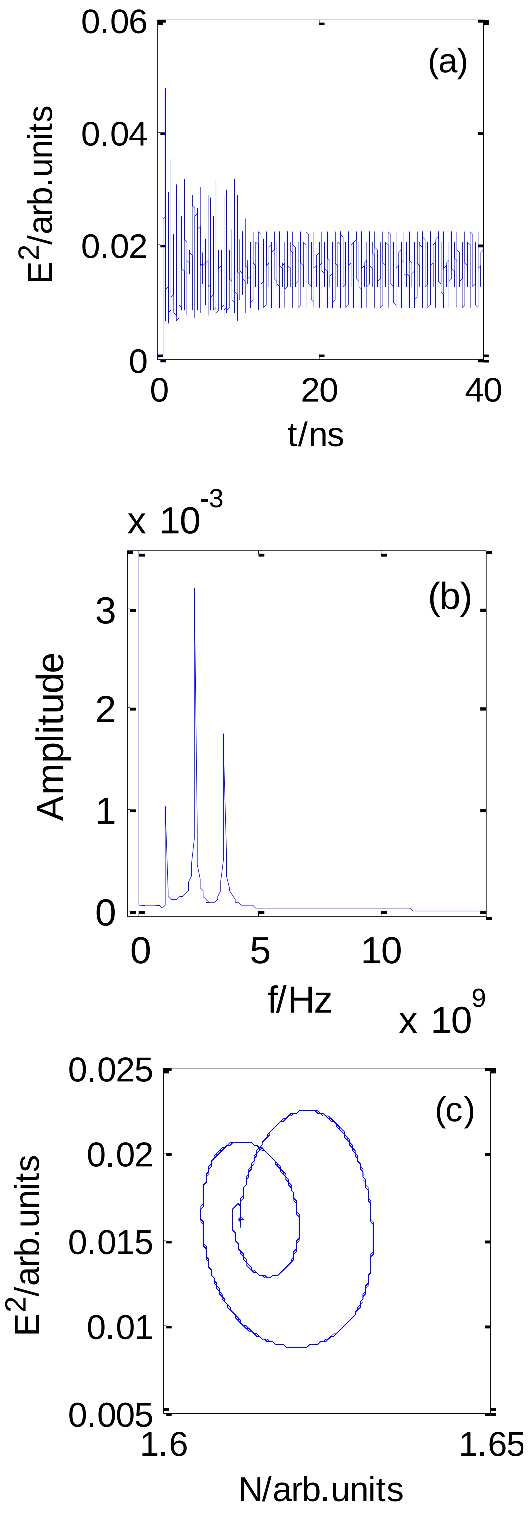

Fig.5. k=0.0216, f=1.191GHz, system is kept to a three-periodic state

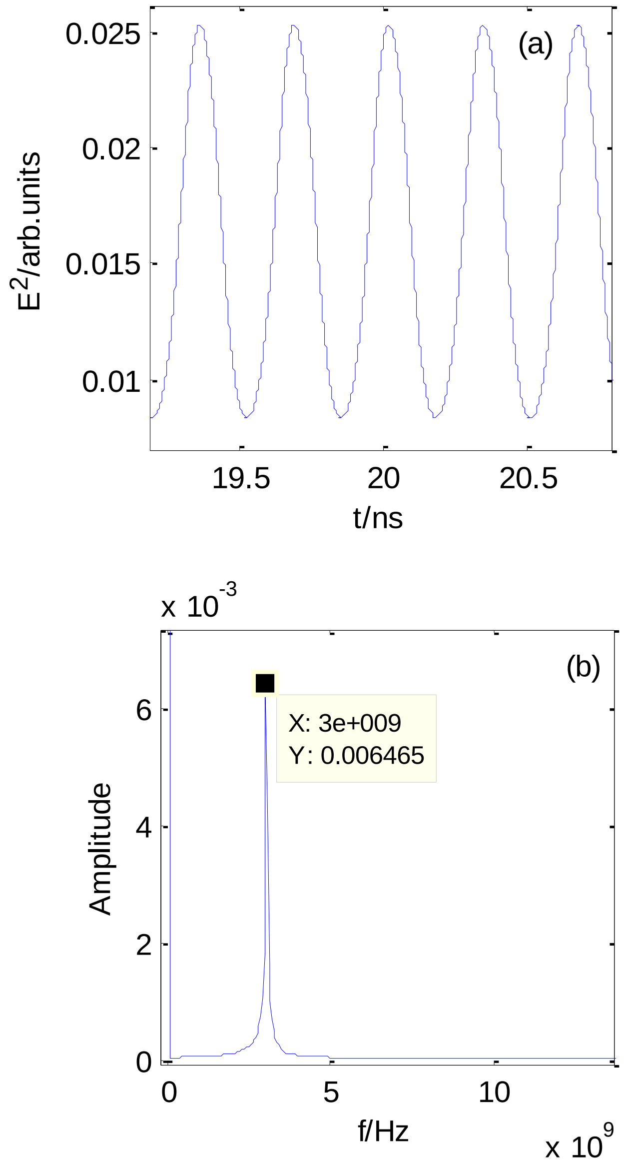

Fig.6 k=0.0216, f=1.51GHz, the amplification map (a), the spectrum (b)

Second, select another optical injection coefficient k (k=0.0424). Fig. 7 and Fig. 8 show that when the modulation frequency is 1.51GHz and 2.96GHz, the system is separately controlled to single-periodic state and dual-periodic state.

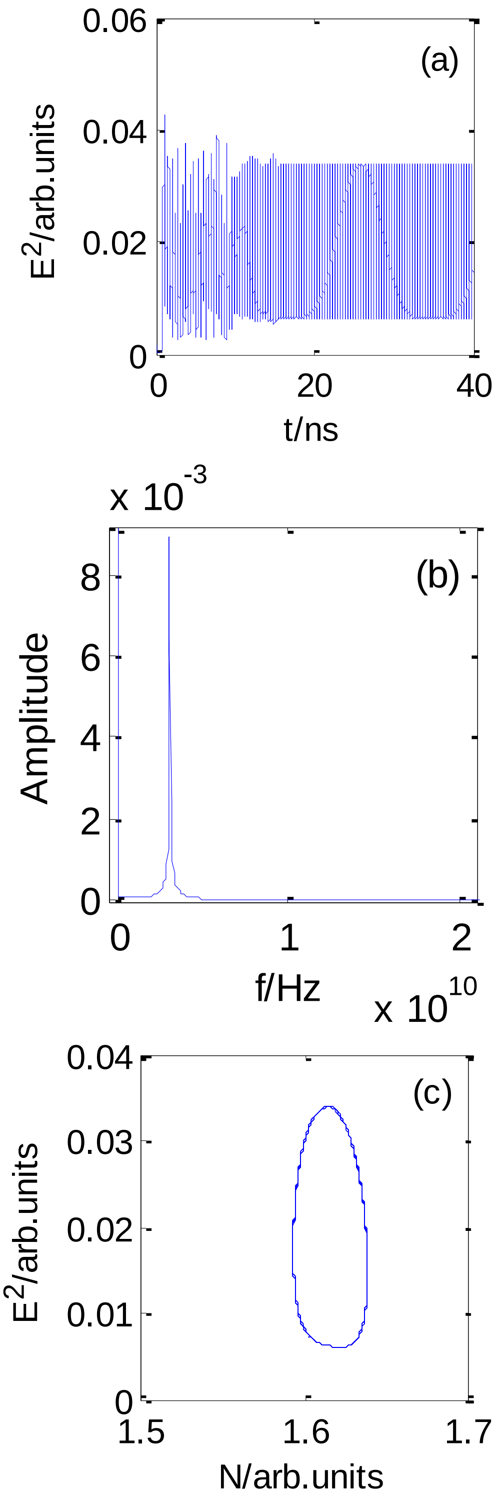

Fig. 7. k=0.0424, f=1.51GHz, system is kept to a single-periodic state

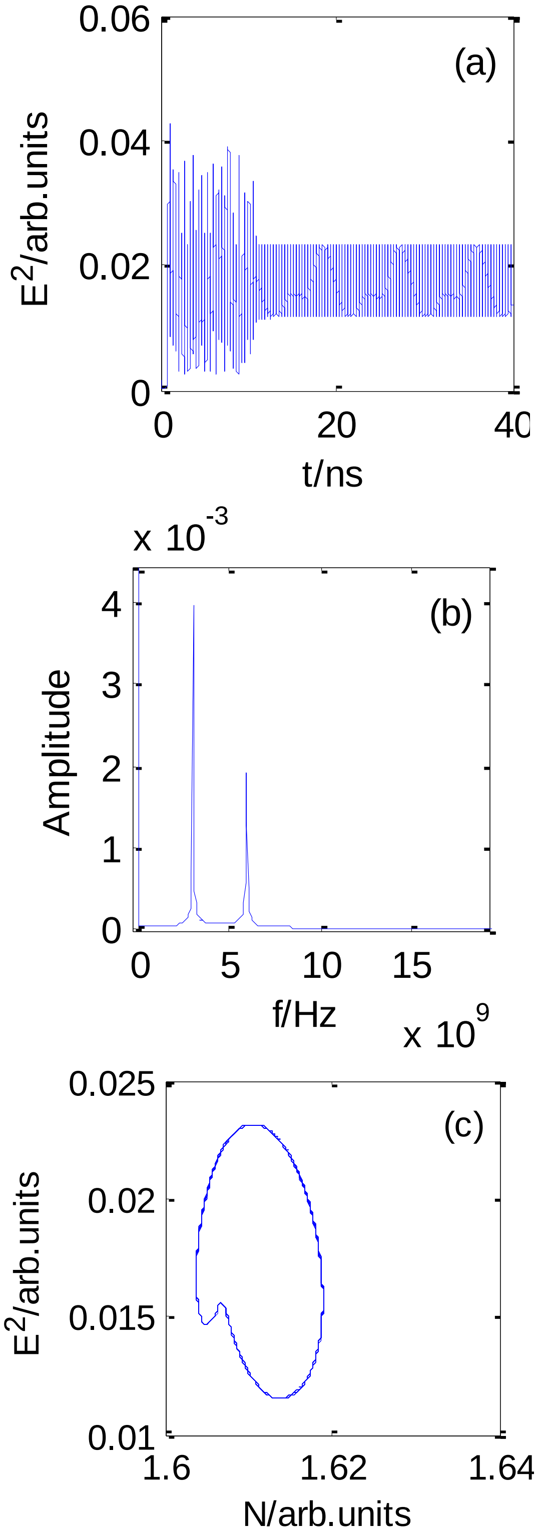

Fig.8. k=0.0424, f=2.96GHz, system is kept to a dual-periodic state

Finally, select the optical injection coefficient k (k=0.05). Fig.9 shows that when the modulation frequency is 6.17GHz, the system is controlled to three-periodic state. Compared with the two previous optical injection coefficients, while the optical injection coefficient increases, corresponding increases in the modulation frequency, but the states that system can control will decrease. Compared with the first and the second optical injection coefficient, the modulation frequency is significantly higher than them, and the system can only be kept in a cycle of state.

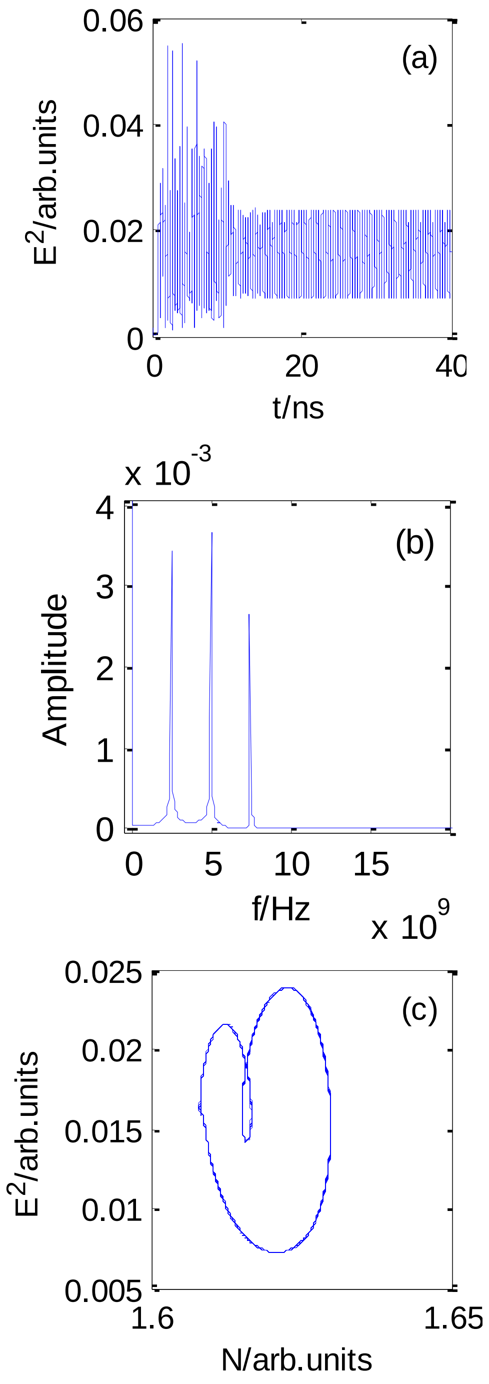

Fig.9. k=0.0500, f=6.17GHz, system is kept to a three-periodic state

4. Conclusions

The paper study the nonlinear dynamics of a semiconductor laser under external optical injection, a periodic control method by external optical injection strength in the semiconductor laser is presented. The method can effectively control the system from chaotic state to periodic state，compared with other methods, it can control the chaos to less periodic and more stable state, it is simple and effective. It's meaningful to improve the efficiency of the laser output and inhibit the generation of chaos, and even more important, it is helpful for study of chaos-control and injection mode-locked laser.

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