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Generating of Chaotic Signals by using Semiconductor Laser with Optical Feedback

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Abstract

This paper addresses theoretically generating the chaotic signals by using semiconductor laser diode of 1550 nm with optical feedback. The performance of a semiconductor laser subjected to a delay optical feedback was investigated using rate equations that describe the temporal variation of photon density, carrier density, and the phase of the lasing field. The simulation results show how semiconductor lasers are sensitive to external optical perturbations and how rich chaotic signal with large information can be generated with controlled optical feedback.

توليد الاشارات الفوضوية باستخدام ليزر شبه الموصل وبتقنية التغذية الضوئية الرجعية

الخلاصة

هذا البحث يتناول نظريا توليد الاشارات الضوئية الفوضوية باستخدام ليزر شبه الموصل بطول موجي 1550 نانومتر وبتقنية التغذية الضوئية الرجعية. تم انجاز اداء ليزر شبه الموصل بوجود التغذية الضوئية الرجعية باستخدام معادلات ضخ الليزر التي تصف التغيير المرحلي لكثافة الفوتونات والطور للمجال الليزري. اوضحت نتائج التحليل مدى حساسية الليزرات شبه الموصلة للاضطرابات الضوئية الخارجية وكيف تم الحصول على الاشارة الفوضوية بالسيطرة على التغذية الضوئية الرجعية.

Introduction

Chaotic optical communication system (COC) was a novel communication scheme that utilizes optical chaotic waveform to transmit information at high bit rate. Its potential applications include secure communications and spread-spectrum communications. The semiconductor laser is well suited for COC systems since the internal laser oscillation was easily interfered with a field from optical injection or optical feedback [1]. Communications using chaotic waveforms as 'carriers' of information promise possible advantages over traditional communications strategies [2,3]. Efficient use of the designated bandwidth of a communication system, leading to expanded information bearing capacity or an increased number of channels for the system.

Ability of a chaotic communication system to utilize, rather than avoid, the

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inherent non linearity of communication devices. A chaotic communication system allows large-signal modulation for message encoding and eliminates complicated measures to maintain linearity.

Chaotic characteristics of a semiconductor laser operating with optoelectronic feedback have been addressed extensively in the literature [4,5]. Recently, ther was increasing interest in the characteristics of a semiconductor laser subjected to optical feedback which indicates the possibility of achieving high speed chaotic behavior [6,7]. The paper gives a theoretical inspection for such behavior.

Semiconductor laser Rate Equations

The operating characteristics of semiconductor laser are well described by a set of rate equations that govern the unteraction of photons and electrons inside the active region. For a single mode laser, these rate equations are [8,9]

$$\frac{dE(t)}{dt} = \frac{1}{2} G_N \left(N(t) - N_{th}\right) E(t) \quad \ldots (1)$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2} \alpha G_N \left(N(t) - N_{th}\right) \quad \ldots (2)$$

$$\frac{dN(t)}{dt} = \frac{I}{qV} - \frac{N(t)}{\tau_c} - G_N\left(N(t) - N_o\right)\left|E(t)\right|^2 \quad (3)$$

Where

N=carrier density

E= Electric field in the active region (v/m)

N_{th}= Carrier density at threshold (m^{-3})

ϕ = Phase of the electric field (rad)

α = Linewidth enhancement factor

I = Injected current (mA)

q = Electron charge (c)

V= Active region volume (m^3)

τ_c = Carrier life time (ns)

N_o = Carrier density at transparency (m^{-3})

$$G_N = \frac{\partial G}{\partial N}$$

Consider a single-mode semiconductor laser subject to optical feedback through an external mirror as shown in Figure 1. In this case, the phase of the feedback electric field of the optical signal plays a key role in determining the dynamic of the laser diode (LD). Therefore, complex electric field with amplitude $|E|$ and phase ϕ is used rather than photon density in the laser rate equations. To generate chaotic pulses in the laser diode, the terms shown below are added to the right hand side of eqns. 1 and 2, respectively [10]

$$\frac{k_f}{\tau_{in}} E(t-\tau)\cos\theta(t) \quad \ldots..(4)$$

$$-\frac{k_f}{\tau_{in}} \frac{E(t-\tau)}{E(t)} \sin\theta(t) \quad \ldots..(5)$$

Where

k_f =Feedback coefficient

τ = Round trip time in the external laser cavity

$$\tau = \frac{2L}{c}$$

c =Speed of light in vacuum

$\theta(t) = \omega_o\tau + \phi(t) - \phi(t-\tau)$

ω_o = Laser frequency at solitary oscillation

τ_{in} =Round trip time in the internal laser cavity

These terms represents the optical feedback effect on the laser diode. Therefore, eqns. 1 and 2 become [10]

$$\frac{dE(t)}{dt}=\frac{1}{2}G_N\left(N(t)-N_{th}\right)E(t)+\frac{k_f}{\tau_{in}}E(t-\tau)\cos\theta(t) \quad (6)$$

$$\frac{d\phi(t)}{dt}=\frac{1}{2}\alpha G_N\left(N(t)-N_{th}\right)-\frac{k_f}{\tau_{in}}\frac{E(t-\tau)}{E(t)}\sin\theta(t) \quad \dots (7)$$

$$\frac{dN(t)}{dt}=\frac{I}{qV}-\frac{N(t)}{\tau_c}-G_N\left(N(t)-N_o\right)\left|E(t)^2\right| \quad \dots .(8)$$

The feedback coefficient k_f is computed from [11].

$$k_f=\left(1-r_o^{\,2}\right)\frac{r}{r_o} \quad \dots .(9)$$

where

r_o = Amplitude reflectivities for the front and back facet (the amplitude reflectivities of the front and back facet are assumed to be the same).

r = Amplitude reflectivity of the external mirror. The threshold current is calculated from eqn. (10)

$$I_{th}=\frac{qVN_{th}}{\tau_c} \quad \dots .(10)$$

The output power emitted from each facet can also expressed as [11]

$$P_{out}=\frac{1}{2}\hbar\,\omega_o\upsilon_g\alpha_m VE^2 \quad .(11)$$

Where

$$\hbar=\frac{h}{2\pi}$$

$h=$ Planck's constant

υ_g =Group velocity

α_m =Linewidth enhancement factor

Results

When semiconductor lasers are subject to optical feedback their output dynamics often become chaotic. The external mirror and external cavity length play an important role in the chaotic dynamics of semiconductor lasers. Chaotic dynamics occur even for a small change of the external mirror position, compatible with the optical wavelength (λ). For a small change, the laser output shows periodic undulations (period of λ/2) and exhibits a chaotic bifurcation within the period. Actually, there is also hysteretic either for an increase or decrease of the external cavity length. The parameters values used in the computations are listed in Table 1 [12] and they are related to a semiconductor laser operating at wavelength of 1550nm. Figure 2 illustrates the flowchart used for these calculations.

When L =15 cm and r =1%, $|E(t)|$, $\phi(t)$, output power, $N(t)$, and the attractor according to the eqns. 6-8 are shown in Figures. 3(a-e).

The calculations are repeated for L =20 cm and r= 1%, the results are shown in Figures. 4(a-e). When L=30 cm and r = 1.2%, the parameters $|E(t)|,\phi(t)$, output power, $N(t)$, and the attractor are as shown in Figures. 5(a-e). When L is fixed at 30cm, and the reflectivity r increases to 1.5% the parameters $|E(t)|, \phi(t)$, output power, $N(t)$, and the attractor are as shown in Figures. 6(a-e), in this case the chaotic signals are generating. From Figures 3-6 it is observed that the system evolves into chaos by varying the external cavity length and the external mirror reflectivity. The external cavity length is varied from 15cm to 30cm, and the external mirror reflectivity is varied from 1% to 1.5% ,this corresponds to the change of delay time (τ) and optical feedback coefficient k_f where $\tau = 2L/c$ and $k_f = (1-r_o)r/r_o$. The results are periodic solutions, sub harmonic solutions, and chaos. Such phenomenon is one of the generic properties of the delay differential system; the output evolves into stability with the increase of the delay time.

Conclusions

The main conclusions from this study are

(i) A rich variety of chaotic behavior can be obtained by varying external cavity length, optical feedback coefficient k_f, and external mirror reflectivity. Further, the delayed optical feedback can offer periodic solutions, sub harmonic solutions, and chaotic solutions.

(ii) For the system structure parameters used in the simulation, the best values of external mirror reflectivity and the external cavity length that make the system generates chaotic signals are 1.5% and 30 cm respectively when the lasers are biased at 1.4 of the threshold current.

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Table (1) Parameters values of 1550nm semiconductor laser used in the simulation [12].

Symbol	Parameter	Value
λ	Laser wavelength	1550nm
α	Linewidth enhancement factor	3
I_{th}	Threshold current	20.5 mA
I	Injection current	1.4*Ith
G_N	Gain coefficient	8.4*10-13m3 s-1
N_{th}	Threshold carrier density	2.018*1024 m-3
N_o	Carrier density a transparency	1.400*1024 m-3
V	Active region volume	1.2*10-16m3
τ_c	Carrier life time	2.04 ns
τ_{in}	Round trip time in laser cavity	8ps
$f_{o,r,t}$	Transmitter-Receive frequency at free running	384.615THz
r_o	Amplitude reflectivities for the front & back facet	0.556

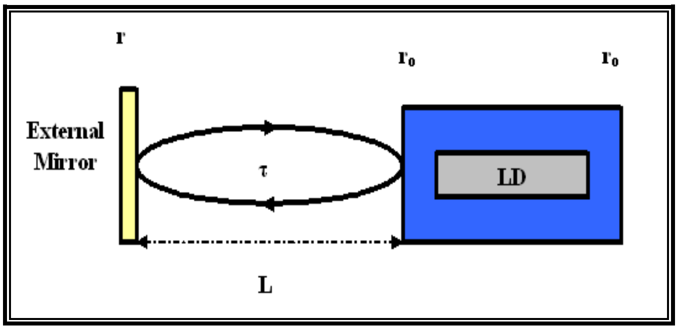


Figure (1) Schematic diagram of the semiconductor laser with external optical feedback.

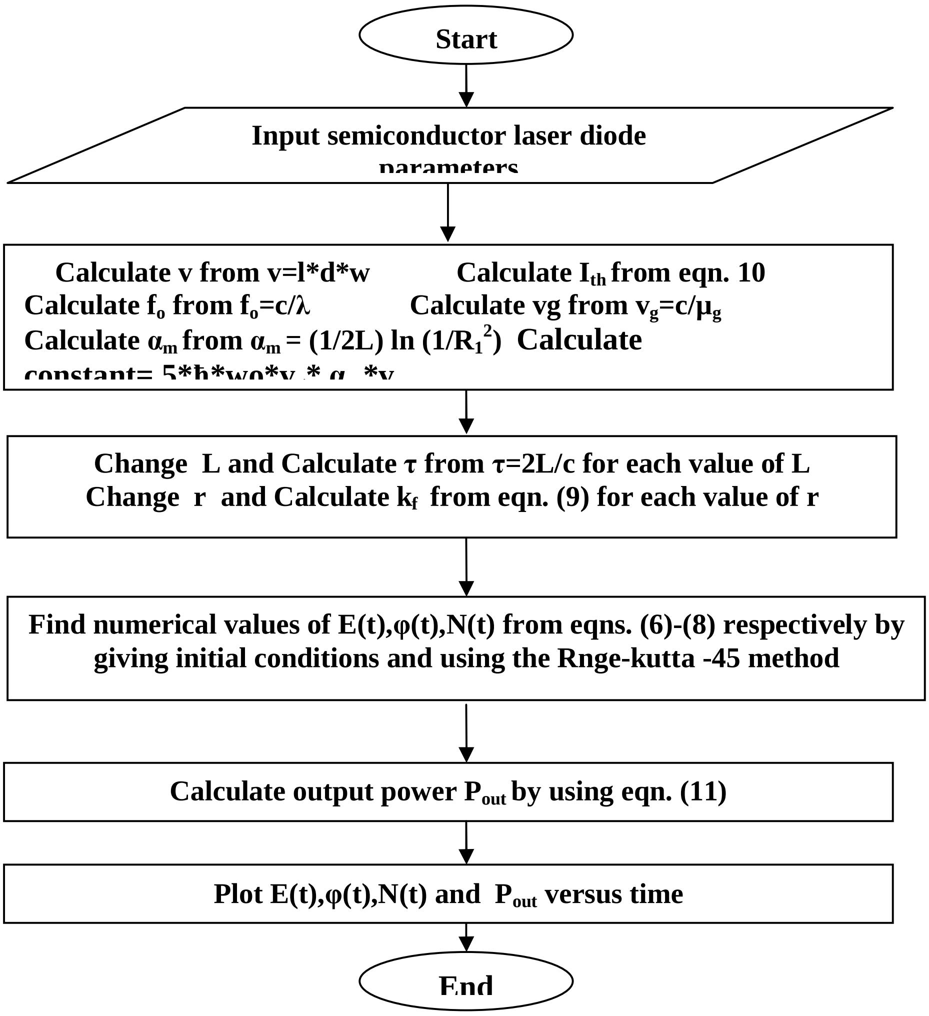


Figure (2) Flow chart of the generation chaotic signal program

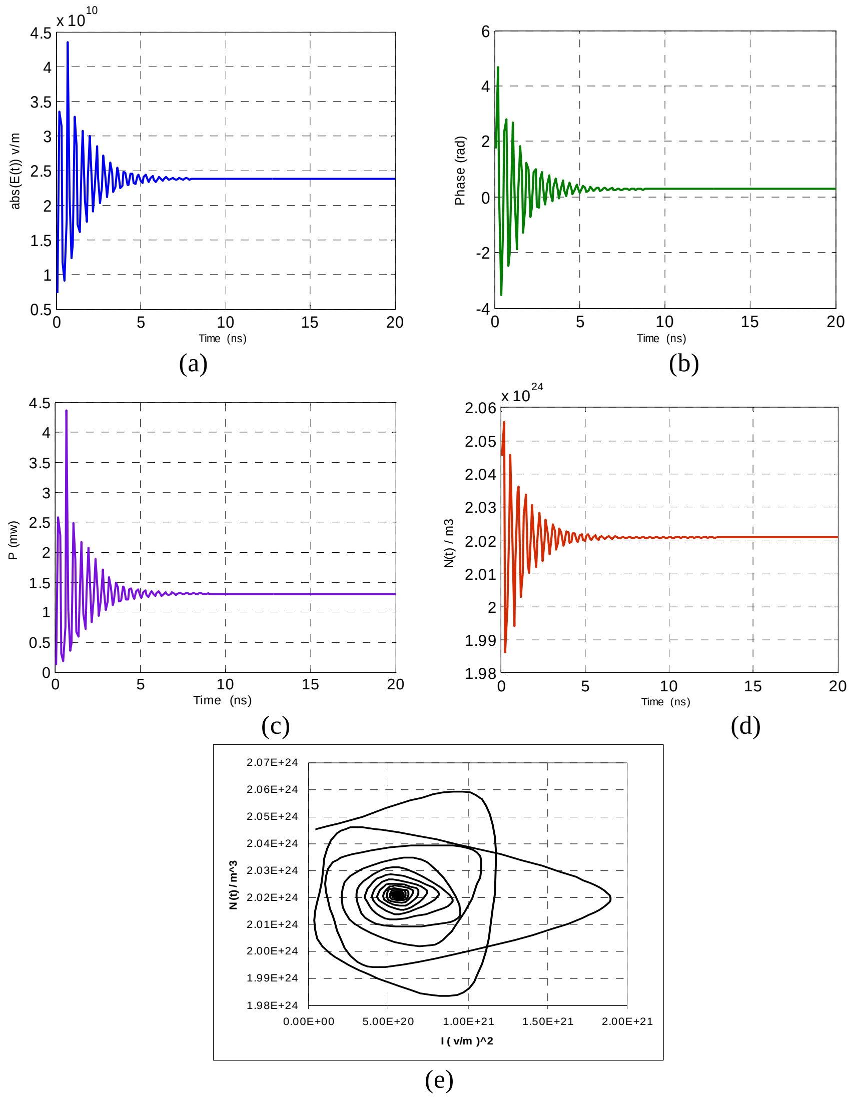


Figure (3) Characteristics of semiconductor laser with optical feedback when r =1% and L =15cm (a) Electric field (b) Phase of electric field (c) Output power (d) Carrier density (e) Attractor.

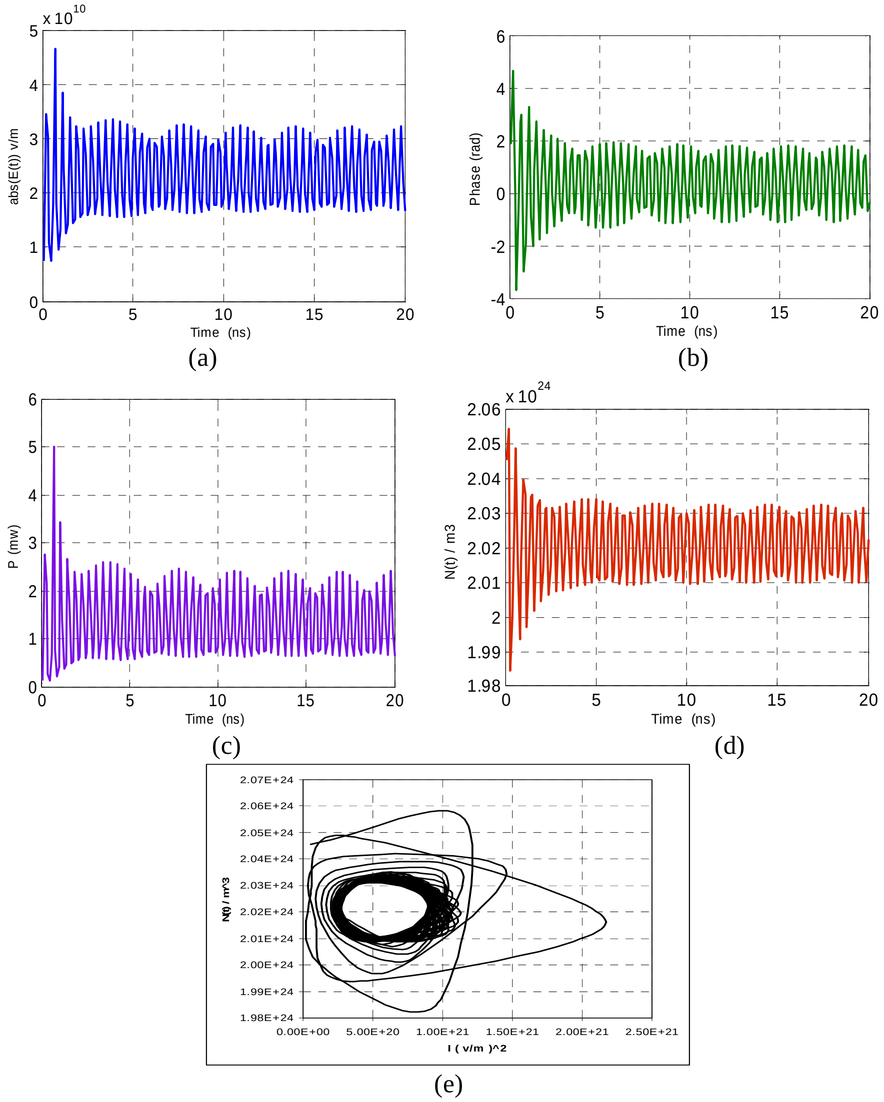
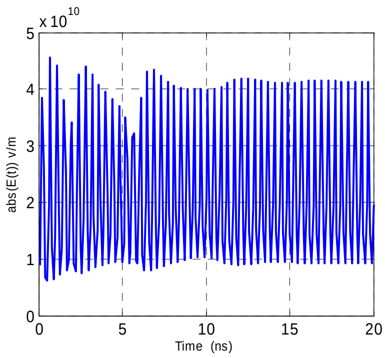
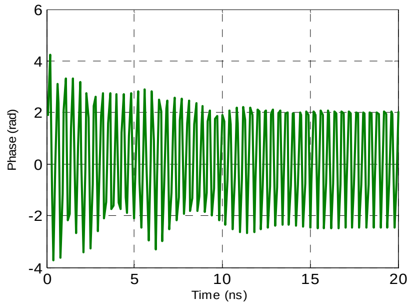


Figure (4) Characteristics of semiconductor laser with optical feedback when r =1% and L =20cm (a) Electric field (b) Phase of electric field (c) Output Power (d) Carrier density (e) Attractor.



(a)



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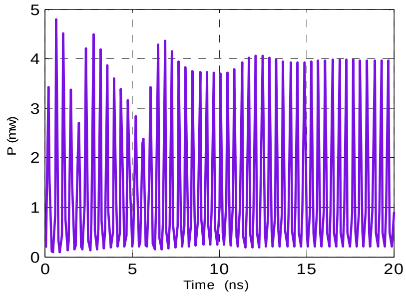

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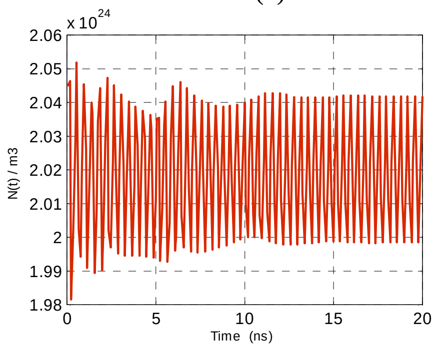
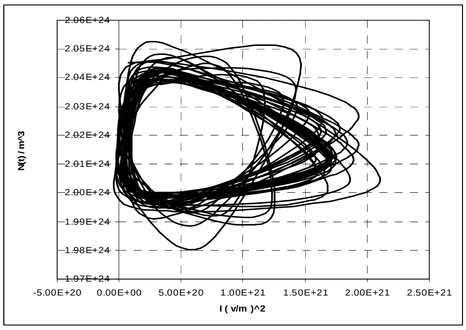


(b)



(e)

Figure (5) Characteristics of semiconductor laser with optical feedback when L =30cm and r =1.2% (a) Electric field (b) Phase of electric field (c) Output power (d) Carrier density (e) Attractor.

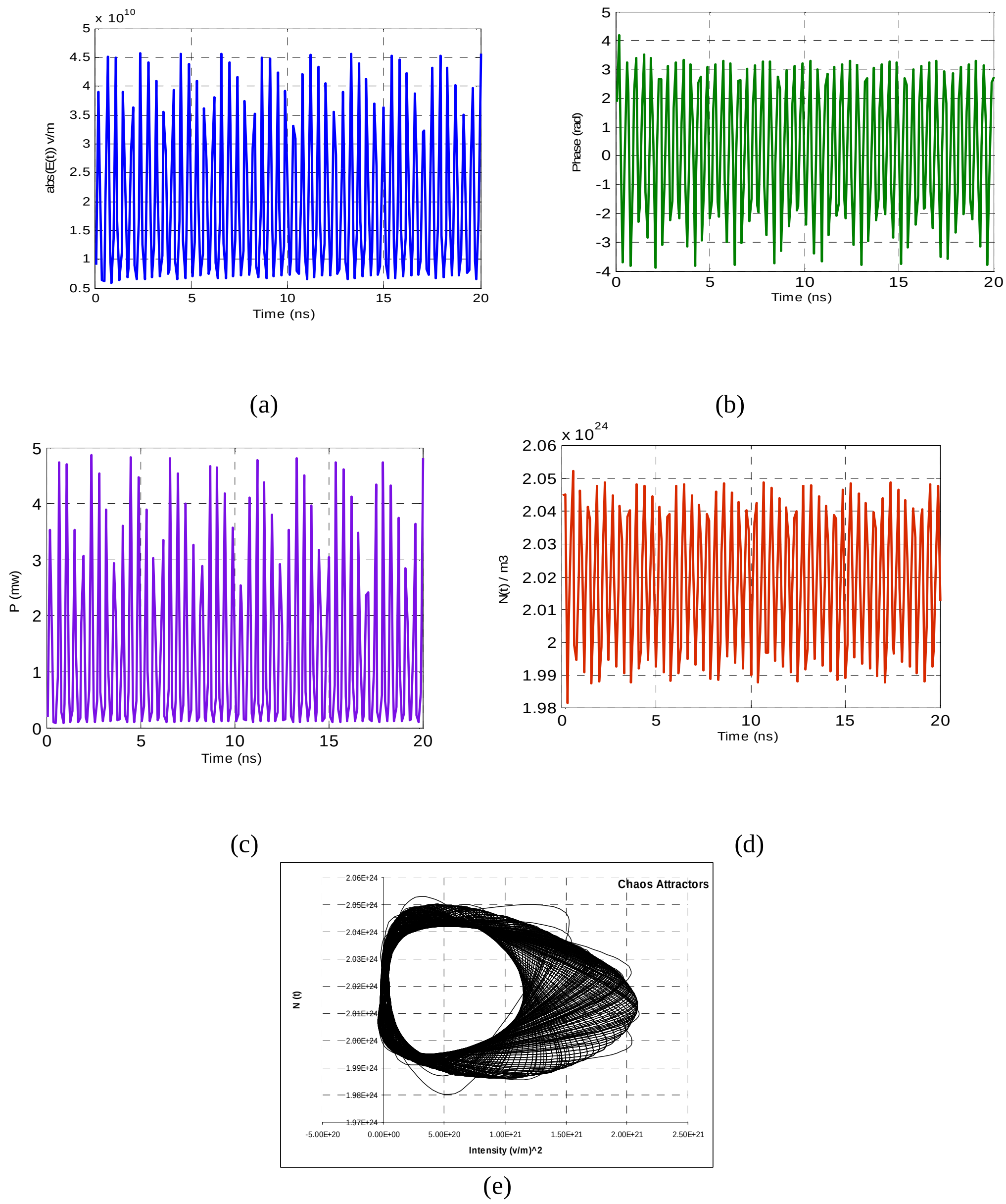


Figure (6) Characteristics of semiconductor laser with optical feedback when L =30cm and r =1.5% (a) Electric field (b) Phase of electric field (c) Output power (d) Carrier density (e) Attractor.