Period-control and chaos-anti-control of a semiconductor laser using the twisted fiber

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(Received 13 February 2016; revised manuscript received 23 April 2016; published online 19 July 2016)

A novel semiconductor laser system is presented based on a twisted fiber. To study the period-control and chaos-anti-control of the laser system, we design a type of optic path as a control setup using the combination of the twisted fiber and the polarization controller while we present a physical dynamics model of the delayed dual-feedback laser containing the twisted fiber effect. We give an analysis of the effect of the twisted fiber on the laser. We use the effects of the delayed phase and the rotation angle of the twisted fiber and the characteristics of the system to achieve control of the laser. The laser is deduced to a stable state, a double-periodic state, a period-6 state, a period-8 state, a period-9 state, a multi-period state, beat phenomenon, and so on. The periodic laser can be anti-controlled to chaos. Some chaos-anti-control area is found. The laser system is very useful for the study of chaos-control of the laser setup and the applications of some physics effects.

Keywords: chaos, anti-control, laser, twisted fiber

PACS: 05.45.Gg, 05.45.Pq, 02.30.Yy, 42.60.By **DOI:** 10.1088/1674-1056/25/9/090504

1. Introduction

Chaos is a kind of nonlinear phenomenon. A chaotic system is sensitive to the initial conditions and shows some random behaviors, different starting conditions result in many different kinds of dynamic orbits. It is very difficult to predict the chaotic long-term behavior.[1–3] However, characteristics and laws behind chaos are gradually discovered.[4–8] In the 1990s, the "OGY" chaos-control method was presented,[1] the study of chaos-control has been rapidly developed;[6–11] the parameter chaos control, the adaptive chaos control, the fuzzy chaos control, and so on have been presented.

Nonlinear devices, e.g., semiconductor lasers, are easily subjected to external feedback and can be destabilized to chaotic oscillation.[3–8] For applications requiring stable operation, the chaos control is very important. On the other hand, in the last two decades, some applications of chaos have been proposed and developed, such as optical chaos communication, chaotic radar, chaotic OTDR, and physical random number generation.[12–15] Therefore, the generation of chaos laser, i.e., chaos-anti-control of laser, becomes equally important. We can use some techniques to suppress chaos laser or guide laser into some states.[6–11] Many chaos-control methods are proposed to suppress or stabilize chaotic laser. There are the current perturbation method, the delay feedback method, the injection period signal method, the phase modulation method, the double split feedback method, the injection chaotic signal method, and so on.[6–11,16–18]

A twisted fiber has the birefringence property. The polarization light passed through the twisted fiber results in a delayed phase, an optical rotation, or an optical axis deflection. Using the characteristic of the twisted fiber, we present a novel semiconductor laser system with a twisted fiber as the optical delayed feedback path. It is a novel idea to introduce some physics effects to guide the laser behavior or chaos-anti-control of the laser. It will be a new research area of chaos-control or laser techniques by using physics characteristics and especial effects. We focus on the chaos-anti-control and dynamics in the laser by introducing the physics effects of the twisted fiber. The laser system is very helpful to study other laser systems and chaos-control.[19]

2. Physical model

The delay negative feedback semiconductor laser with an external cavity is a nonlinear optical system, which has been widely studied in theory and experiment. As a result of the optical re-injection of the delayed feedback, the laser has some stable or unstable nonlinear phenomena, such as a period, a multi-period and bifurcation or chaos.[6–10] In order to structure a new laser system with delayed dual-feedback characteristic and study the control or anti-control laser, we design first a controllable ring path using a twisted fiber to structure a new combination of the delayed feedback and ring laser system. Figure 1 shows a schematic block of the laser using a twisted fiber. In order to simplify the theory model, the laser may be considered as single-polarization lasing.

Here, the optical path of the laser system is designed as follows. A beam of light after PC_1 is divided into two beams by the beam splitter BS, a bunch of light is reflected by the semireflecting mirror M_1 back to the laser, the optical path of the laser and the mirror M_1 constitute the known external cav-

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ity delayed feedback laser. Under certain conditions, the laser can show cycle or chaos operation. Another bunch of light passes through the twisted fiber, and then through the polarization controller PC_2 and re-injects to the laser via the mirror M_2, where PC_2 controls the polarization direction and the re-injection level of the light because the polarization rotation of light occurs when the light passes through the twisted fiber. The combining of the fiber and PC_2 is used as a control.

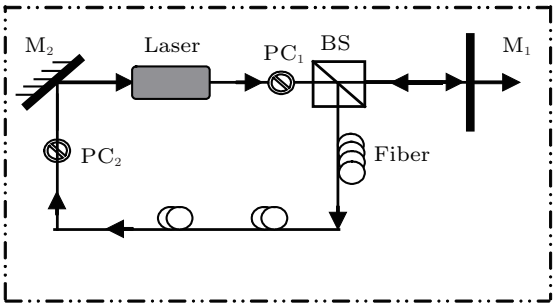


Fig. 1. Schematic block of the laser using a twisted fiber. M_1 is the semireflecting mirror, M_2 is the plane mirror, BS is a beam splitter, and PC_1 and PC_2 are two polarization controllers.

The twisted fiber is spinning at rate ξ and the fiber has birefringence $\Delta\beta$, the light passes through the fiber; at length z, the phase delayed $R(z)$, the rotation angle $\Omega(z)$, and the optical axis deflection angle $\Phi(z)$ can be obtained as[20]

$$R(z) = 2\sin^{-1}\left(\frac{\rho}{\sqrt{1+\rho^2}}\sin\gamma z\right), \tag{1a}$$

$$\Omega(z) = \xi z + \tan^{-1}\left(-\frac{1}{\sqrt{1+\rho^2}}\tan\gamma z\right), \tag{1b}$$

$$\Phi(z) = \frac{\xi z - \Omega(z)}{2} \pm \frac{m\pi}{2}, \quad (m = 0,1,2,3,\ldots), \tag{1c}$$

with

$$\rho = \frac{\Delta\beta}{2(\xi - a)}, \quad \gamma = \frac{\sqrt{(\Delta\beta)^2 + 4(\xi - a)^2}}{2}, \quad a = G\xi,$$

where a is the photoelasticity factor and G is the coefficient.

Next, we focus on the following two cases in this work.

1) For a low twisted rate $\xi \ll \Delta\beta$, we obtain $\Phi(z) \approx 0$, namely, the optical axis cannot vary. The delayed phase and the rotation angle are obtained as

$$R(z) \approx \Delta\beta z, \tag{2a}$$

$$\Omega(z) \approx \xi z. \tag{2b}$$

The polarization rotates synchronously with the fiber lengthening.

2) For a larger twisted rate $\xi \gg \Delta\beta$, the delayed phase and the polarization rotation are obtained as

$$R(z) \approx \frac{\Delta\beta}{\xi - a}\sin[(\xi - a)z], \tag{3a}$$

$$\Omega(z) = az. \tag{3b}$$

Here the strong photoelasticity produced by the larger twisted fiber suppresses the birefringence.

We consider the twisted fiber effects on the laser system, the dynamic equations of the laser with the twisted fiber are obtained as follows:[5–12]

$$\begin{aligned}\frac{\mathrm{d}E}{\mathrm{d}t} &= \frac{1}{2}\left[g(N-N_0) - \frac{1}{\tau_\mathrm{p}}\right]E(t) \\ &\quad + \frac{k_1}{\tau_\mathrm{L}}E(t-\tau_1)\cos[\varphi(t) - \varphi(t-\tau_1) + \omega\tau_1] \\ &\quad + \frac{k_2}{\tau_\mathrm{L}}E(t-\tau_2)\cos[\Omega(z)] \\ &\quad \times \cos[\phi(t) - \phi(t-\tau_2) + \omega\tau_2 + R(z)],\end{aligned} \tag{4a}$$

$$\begin{aligned}\frac{\mathrm{d}\varphi}{\mathrm{d}t} &= \frac{1}{2}\alpha\left[g(N-N_0) - \frac{1}{\tau_\mathrm{p}}\right] \\ &\quad - \frac{k_1}{\tau_\mathrm{L}}\frac{E(t-\tau_1)}{E(t)}\sin[\varphi(t) - \varphi(t-\tau_1) + \omega\tau_1] \\ &\quad - \frac{k_2}{\tau_\mathrm{L}}\frac{E(t-\tau_2)\cos[\Omega(z)]}{E(t)} \\ &\quad \times \sin[\phi(t) - \phi(t-\tau_2) + \omega\tau_2 + R(z)],\end{aligned} \tag{4b}$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = J - \frac{N}{\tau_\mathrm{s}} - g(N-N_0)|E(t)|^2, \tag{4c}$$

where E, φ, and N are the field amplitude, the phase, and the carrier density, respectively. The third terms at the right side of Eqs. (4a) and (4b) are related to the twisted fiber ring path. The laser parameters are introduced as follows: g is the linear gain coefficient, N_0 is the carrier density at transparency, α is the linewidth enhancement factor, J is the drive current density, τ_s is the carrier lifetime, τ_p is the photon lifetime, τ_1 is the external cavity round-trip time, τ_2 is the light trip time in the fiber, $\tau_\mathrm{L} = 2\eta l/c$ is the round-trip time in the laser cavity (where l is the internal cavity length and η is the refractive index of the laser cavity), and ω can be regarded as the frequency. The feedback factor k_1 is written as $k_1 = (1-r_0^2)r_1/r_0$, where r_0 and r_1 are the amplitude reflectivities of the laser exit facet and the external reflector, respectively. The light factor k_2 of the additive optical path is written as $k_2 = (1-r_0^2)r_2/r_0$, where r_2 is the amplitude reflectivity. The effect of the twisted fiber on the laser system is illustrated by the term $k_2\cos[\Omega(z)]$ and the phase delayed $R(z)$, where the term $k_2\cos[\Omega(z)]$ stands for the re-injection level of the light controlled by the polarization analyzer and the polarization direction or the fiber length. The twisted fiber has an obvious effect on the laser system. The twisted fiber length or other parameters can be changed to cause the varieties of the delayed phase, the rotation angle, the delayed time, and the optical feedback level, while the laser will be conduced to show other dynamics behaviors. Multi-parameter control or anti-control of the laser can be achieved. To the best of our knowledge, this laser system is studied here first.

3. Dynamics behaviors in the low twisted rate case

In our numerical simulations, the laser parameters are cited from Ref. [7] and other parameters are taken as $r_0 = 0.556$, $r_1 = 0.006$, and $\tau_1 = 1$ ns. We use the parameters of the twisted fiber in the practical value range, in which we take $\xi \leq 600$ rad/m considering that the twisted fiber will be twisted broken when the spinning rate ξ is higher than $2\pi \times 10^3$ rad/m and $\Delta\beta \leq 160$ rad/m because the modern optical fiber technology can produce $\Delta\beta$ higher than 200 rad/m. The parameters of the twisted fiber are taken as $\Delta\beta = 60$ rad/m, $G = 0.08$, $\xi = 6$ rad/m. The refractive index is taken as 5/3 and the transmission time τ_2 stands for the twisted fiber length as a control parameter to shift the two parameters of the delayed phase and the rotation angle. The factor r_2 related to the feedback level and the factor τ_2 related to the twisted fiber length as the control parameters are adjusted. Figure 2 shows a periodic state of the laser when the twisted fiber is not present, the laser oscillates periodically at 1.95 GHz after 20 ns.

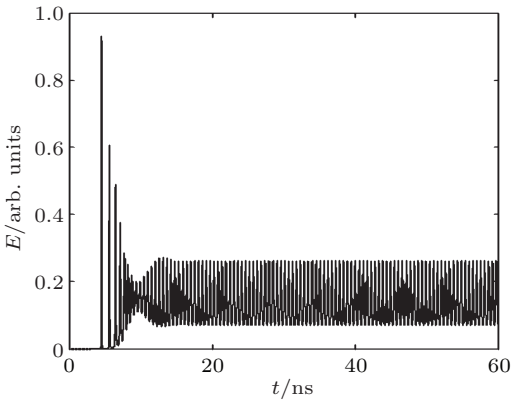


Fig. 2. The laser emits a periodic pulse after 20 ns.

When the control operation is carried out and the control parameters are taken as $r_2 = 0.008$ and $\tau_2 = 2$ ns, the laser is conduced to show a beat after 20 ns while the beat frequency is about 0.22 GHz. A comparison of Figs. 2 and 3 illustrates obviously the effect of the twisted fiber on the working state of the laser; this laser shows clearly different dynamics from a delayed feedback laser. The laser with the physics effects of the twisted fiber will show a lot of dynamics behaviors by adjusting the control parameters. It predicts another research field of laser by introducing some physics effects to the laser system.

When the control parameter is taken as $\tau_2 = 5/3$ ns, the laser is conduced to another periodic state after 60 ns, where the original periodic behavior of the laser is affected and its oscillation frequency shifts to 2.1 GHz as shown in Fig. 4. When the parameter is taken as $\tau_2 = 7/3$ ns, the laser is conduced to another periodic state after 30 ns where the laser oscillation frequency is 2.2 GHz as illustrated in Fig. 5. When we take the parameter $\tau_2 = 55/30$ ns, the laser shows a cycle-8 (Fig. 6). By taking $\tau_2 = 56/30$ ns, the laser is controlled to a cycle-9 as shown in Fig. 7.

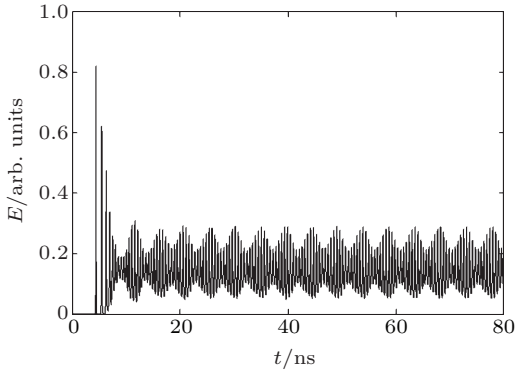


Fig. 3. The laser beats.

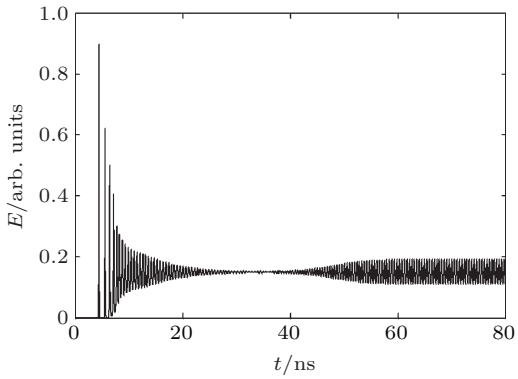


Fig. 4. The laser oscillates periodically after 60 ns.

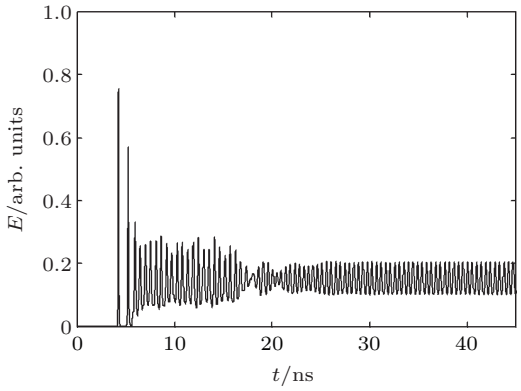


Fig. 5. The laser pulses periodically after 30 ns.

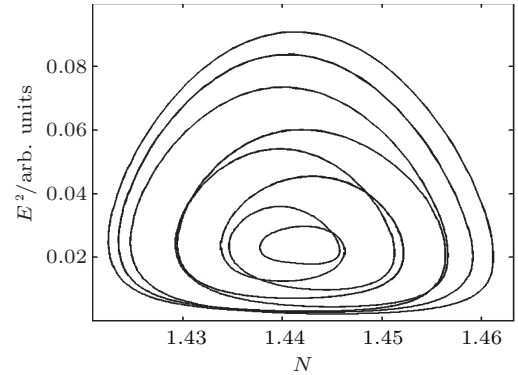


Fig. 6. A cycle-8 orbit.

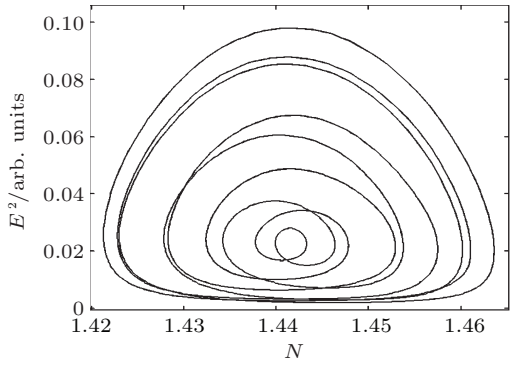


Fig. 7. A cycle-9 orbit.

When we change the parameters to $\xi = 1$ rad/m and $\tau_2 = 5/3$ ns, the laser is controlled to a stable state after 50 ns as shown in Fig. 8. When the parameter $\tau_2 = 4/3$ ns, the laser is conduced to a double-cycle as shown in Fig. 9.

When we take the parameters $\Delta\beta = 100$ rad/m, $\xi = 3$ rad/m, and $\tau_2 = 5/3$ ns, the laser is controlled to a cycle-6 as shown in Fig. 10.

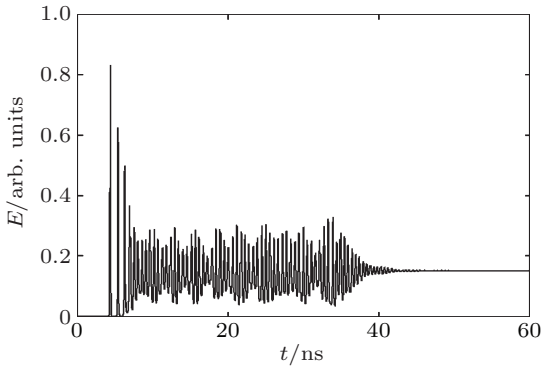


Fig. 8. The laser will output stably after 50 ns.

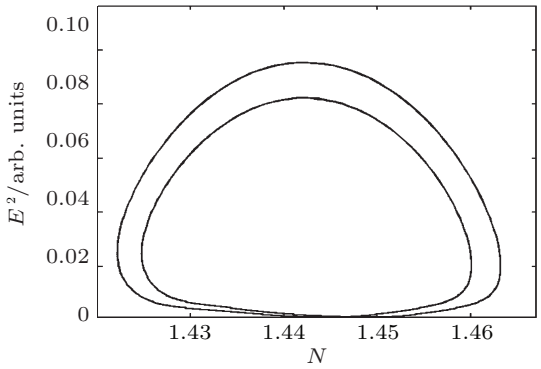


Fig. 9. A double-cycle orbit.

When we take the parameters $\Delta\beta = 160$ rad/m, $\xi = 4$ rad/m, $r_2 = 0.02$, and $\tau_2 = 45/30$ ns, the laser is suppressed to a stable state after 25 ns as illustrated in Fig. 11. When $\tau_2 = 5$ ns, the laser shows chaos. The chaotic attractor and the enhanced spectrum width are shown in Figs. 12(a) and 12(b), respectively. It implies that the laser is anti-controlled to chaos. When we take $\tau_2 = 5/3$ ns, the laser is conduced to a single-periodic state after 30 ns (Fig.13), and the laser oscillation frequency is 1.95 GHz.

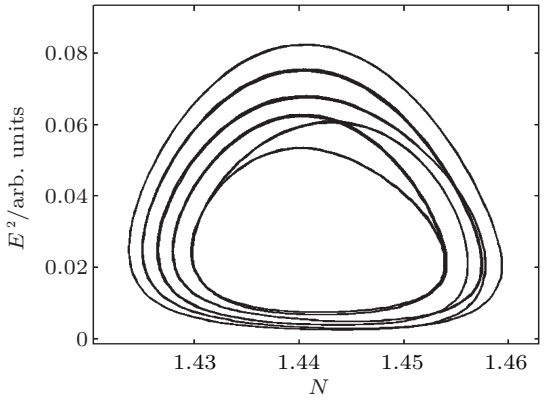


Fig. 10. A cycle-6 orbit.

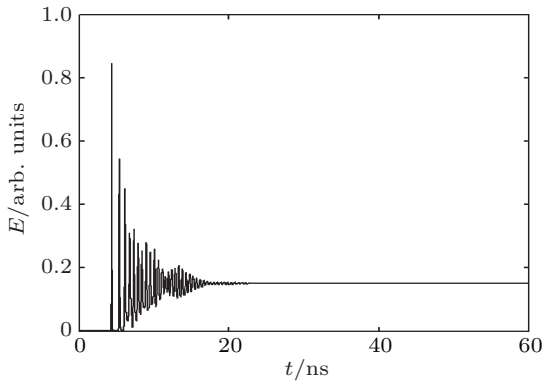


Fig. 11. The laser is in a stable state after 25 ns.

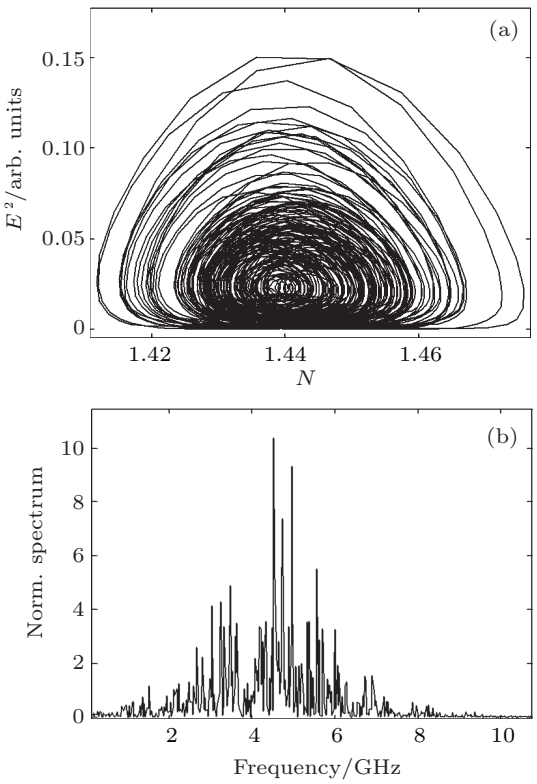


Fig. 12. (a) A typical chaotic attractor and (b) the spectrum.

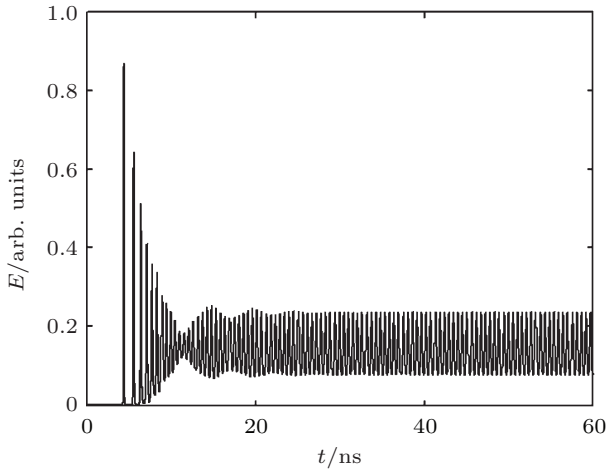


Fig. 13. The laser oscillates periodically after 30 ns.

We find that the laser shows many complex dynamics behaviors by changing the control parameters of the twisted fiber due to a low twisted rate. We can effectively control the laser.

4. Dynamics behaviors in the large twisted rate case

The parameters of the twisted fiber can be taken as $\xi = 600$ rad/m, $\Delta\beta = 60$ rad/m, $G = 0.08$ when the large twisted rate fiber is introduced to the system. Let $r_2 = 0.08$ and $\tau_2 = 45/30$ ns, as shown in Fig. 14, the laser will be in a stable state after 30 ns. With $\tau_2 = 5/3$ ns, figure 15 shows that the laser is a chaotic state. We find that the laser can be controlled to a stable state or anti-controlled to chaos. With $\tau_2 = 2$ ns, the laser shows a periodic behavior (Fig. 16).

When the control parameters are taken as $r_2 = 0.004$ and $\tau_2 = 55/30$ ns, the laser shows a period-15 in Fig. 17. With $\tau_2 = 3$ ns, the laser shows a multi-period in Fig. 18.

We discuss the dynamics behavior changing with the control parameter τ_2 to show a road to chaos. Let $r_2 = 0.012$, we find that the laser is in a period state at a frequency of 2 GHz when $\tau_2 = 1.5$ ns. When $\tau_2 = 5/3$ ns, the laser will operate at a stable state after 20 ns (Fig. 19). Increasing τ_2 to 55/30 ns, the laser will be in another stable state. When $\tau_2 = 2$ ns, the laser is in another period state at a frequency of 1.9 GHz. Increasing τ_2 to 65/30 ns, we find that the laser has a multi-period (Fig. 20). With $\tau_2 = 1.4$ ns, the laser shows a period-15 in Fig. 21. When $\tau_2 = 8/3$ ns, we find that the laser is in a period state at a frequency of 1.8 GHz. We find that the laser can be anti-controlled to chaos when the parameter τ_2 is taken from 85/30 ns to 5 ns. Figures 22(a) and 22(b) show the chaotic behavior of the laser when $\tau_2 = 85/30$ ns. The above results describe roughly a road to chaos from a stable state after some diverse multi-period.

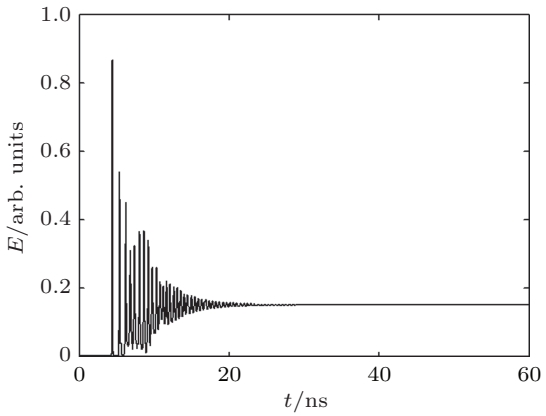


Fig. 14. The laser evolves to a stable state after 30 ns.

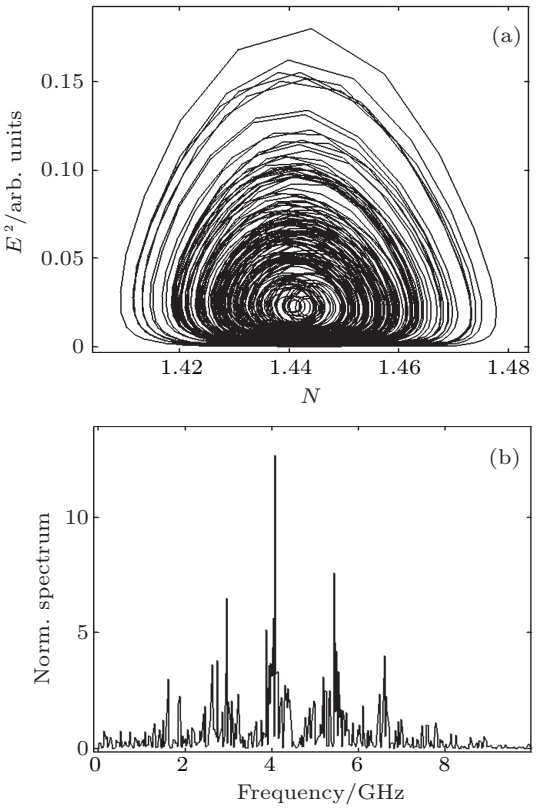


Fig. 15. (a) A chaotic attractor and (b) the spectrum.

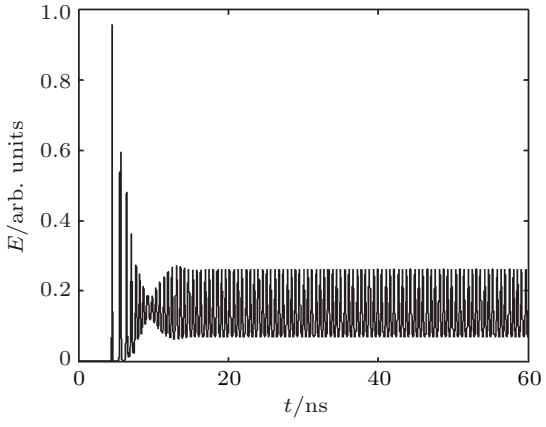


Fig. 16. The laser oscillates periodically after 20 ns.

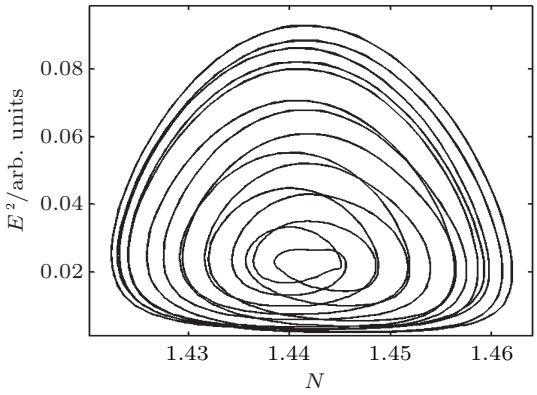


Fig. 17. A cycle-15 orbit.

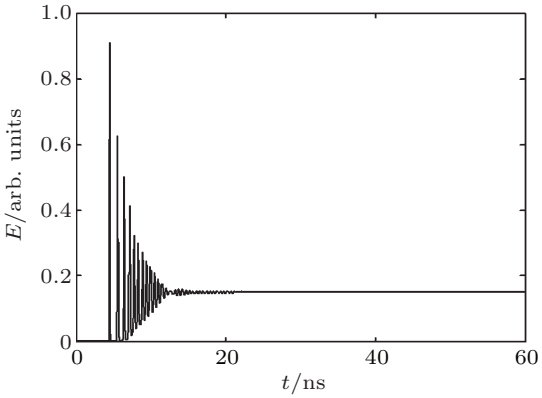


Fig. 19. The laser is controlled to a stable state after 20 ns.

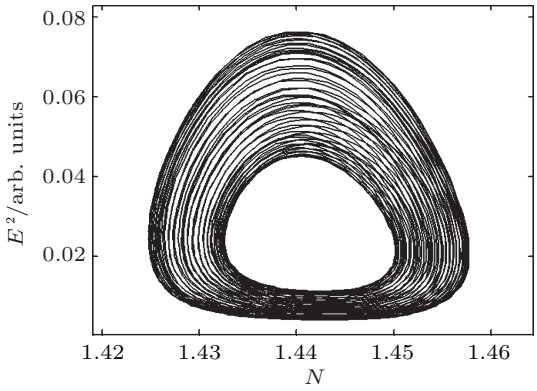


Fig. 18. A multi-period belt.

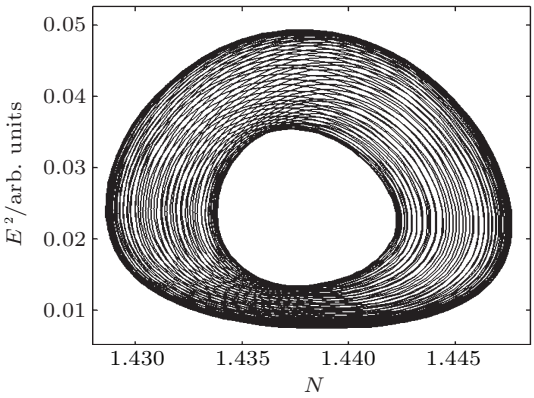


Fig. 20. Another multi-period belt.

Figure 23(a) gives the operating state of the system as a delayed dual-feedback laser without considering any effects of $\Delta\beta$, R, and Ω of the twisted fiber feedback loop, where $\tau_1 =$ 1 ns, $r_1 = 0.006$, $\tau_2 = 1.1$ ns, and $r_2 = 0.008$. Figure 23(b) gives the operating state of the system considering the effects of the twisted fiber feedback loop, where $\tau_1 = 1$ ns, $r_1 = 0.006$, $\tau_2 = 1.1$ ns, $r_2 = 0.008$, $\xi = 600$ rad/m, $\Delta\beta = 60$ rad/m, and $G = 0.08$. A comparison of Figs. 23(a) and 23(b) indicates that the function or effect of the twisted fiber on the behavior of the laser is obvious and the laser system shows clearly different dynamics from a delayed dual-feedback laser.

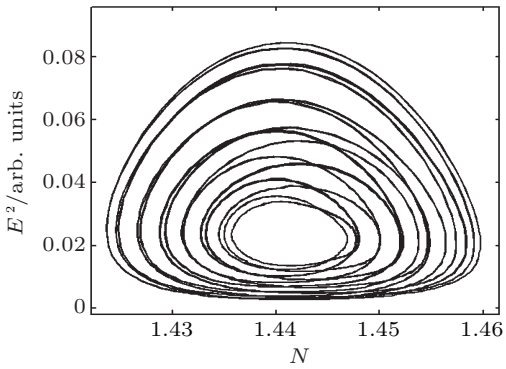


Fig. 21. Another period-15.

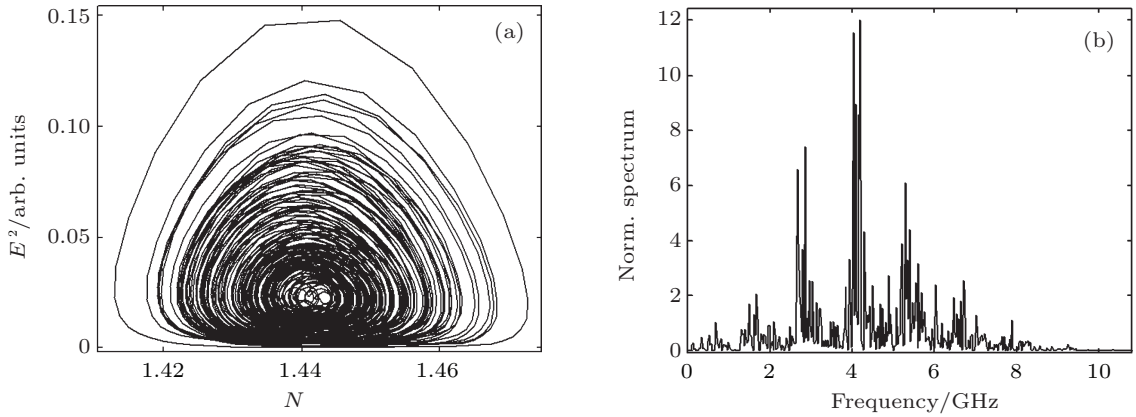


Fig. 22. The laser is anti-controlled to chaos: (a) chaotic attractor and (b) spectrum.

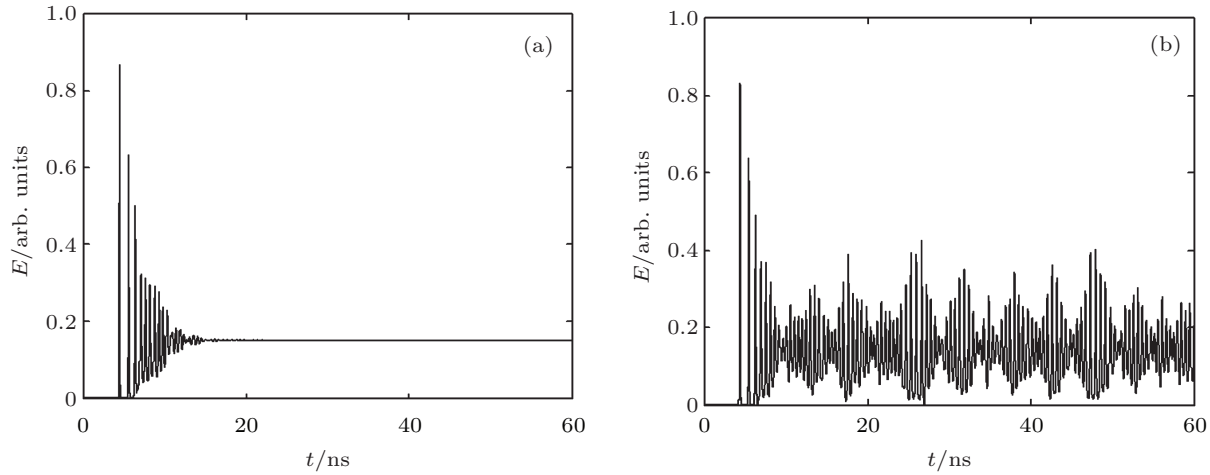


Fig. 23. The laser is stabilized in panel (a), while the laser is anti-controlled to chaos in panel (b).

5. Conclusion

We present a novel semiconductor laser system with a twisted fiber. We study the dynamics behaviors, period-control, and chaos-anti-control of the laser system. The laser is conduced to a stable state, a single-period, a double-period, a period-6, a period-8, a period-9, a multi-period state, beat phenomenon, and so on. The laser can be anti-controlled to chaos. We also give a rough road to chaos.

We find that the laser shows many complex dynamics behaviors by changing the twisted fiber parameters. The laser shows complex dynamics through a road to chaos from a stable state by changing the twisted fiber parameters because the birefringence, phase delay, and rotation of the twisted fiber vary with the fiber length. Our numerical results also show that the large $\Delta\beta$ obviously affects the laser behavior when $\xi \ll \Delta\beta$ and the high ξ results in behavior variety of the laser when $\xi \gg \Delta\beta$. By introducing some physics effects to innovate on laser or control chaos, it is a new research method and is very useful for the study of chaos-control, new laser systems, and other nonlinear systems and their applications.

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