Semiconductor Lasers: Stability, Instability and Chaos

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***Abstract*—Lasers are essentially chaotic system. However, semiconductor lasers are classified into stable class B lasers. Meanwhile, they are easily destabilized by external perturbations (introduction of extra degree of freedom). We discuss chaos in lasers and also instability and chaos in semiconductor lasers. Recently, new semiconductor lasers with extra device structures have been developed and they are essentially unstable lasers without any external perturbations. We also present instabilities in new lasers and the method to control them. Applications of chaotic semiconductor lasers are attractive issues. Here, as an example, we discuss secure communications in chaotic semiconductor lasers.**

Keywords; semiconductor lasers, instability, chaos, control of chaos, chaos communications

I. Introduction

Chaos is the phenomenon of irregular variations of system output derived from models described by deterministic equations. In spite of the models being deterministic, we cannot foresee the future of the output since chaos is very sensitive to the initial conditions: each system behaves completely different every time, even if the difference in the initial state is very small. Chaos can be observed in various fields of engineering, physics, chemistry, economics, and biology. Although the fields are different, some of the chaotic systems can be characterized by similar differential equations. Since lasers are nonlinear systems and are typically characterized by three variables, they are candidates for chaotic systems. Indeed, it was proved in the mid-1970s by Haken [1] that lasers are nonlinear systems similar to the Lorenz model and that they show chaotic behavior in their output power [2].

In this review, we first introduce chaos in laser systems and the classifications of lasers from the viewpoint of the dynamics. Then, we discuss instability and chaos in semiconductor lasers. Recently, many semiconductor lasers with novel device structures have been developed. Those lasers are essentially unstable lasers without external perturbations, since the structures are the introduction of extra degree of freedom. We discuss chaos in those lasers and also present the method of control of the instabilities [2,3]. Chaos is not an unfavorable effect, but it is applicable. For example, self-mixing interference effects and correlation in chaotic semiconductor lasers can be applied to metrology [2-4]. As another example, chaotic signals are used for concealing a message in communications, thus they are used for chaotic secure communications. We show some examples of secure communications in chaotic semiconductor lasers [2-6].

II. Laser Chaos

Laser is theoretically described by three variables; the electric field in the laser, the polarization of the laser medium, and the population inversion to induce the laser oscillation. Using the normalized variables, electric field x, polarization y, and population inversion z, the differential equations to describe the laser oscillation are given as [1,2]

$$\frac{dx(t)}{dt} = -\sigma\{x(t) - y(t)\} \tag{1}$$

$$\frac{dy(t)}{dt} = -(1 - i\delta)y(t) + \{r - z(t)\}x(t) \tag{2}$$

$$\frac{dz(t)}{dt} = -bz(t) + \mathrm{Re}[x^*(t)y(t)] \tag{3}$$

where σ is the decay rate of the field, δ is the atomic detuning, r is the pump parameter, and b is the decay rate of the population inversion. These equations are equivalent to the Lorenz equations, which describe the model of the atmosphere. Therefore, laser is a chaotic system like Lorenz system. Figure 1 shows an example of calculated chaotic oscillations in a laser. The laser exhibits the chaotic oscillation under appropriate parameter conditions (Fig. 1(a)) and its attractor in Fig. 1(b) shows the double scroll trajectory, which is the same one as observed in Lorenz chaos.

Laser is essentially a chaotic system, however, every laser does not show chaotic oscillations. A certain class of lasers shows chaotic instabilities, while the others are stable lasers in their solitary oscillations. According to the scales of the decay rates in the differential equations, lasers are classified into three categories. When we need all of three rate equations to describe a laser, the laser is a chaotic system and it is called a class C laser. Indeed, infrared oscillating gas lasers like NH_3 and Ne-Xe lasers, exhibit chaotic oscillations in their output powers [2]. The second one is a class B laser, in which the time constant of the polarization is very fast and the polarization equation is adiabatically eliminated. Then, the laser is described by the two equations of field and population inversion, and it is a stable laser if there is no external perturbation. The third one is a class A laser, in which only the field equation is enough to describe the system, and it is the most stable class of lasers. Semiconductor lasers (narrow-stripe edge-emitting case) are

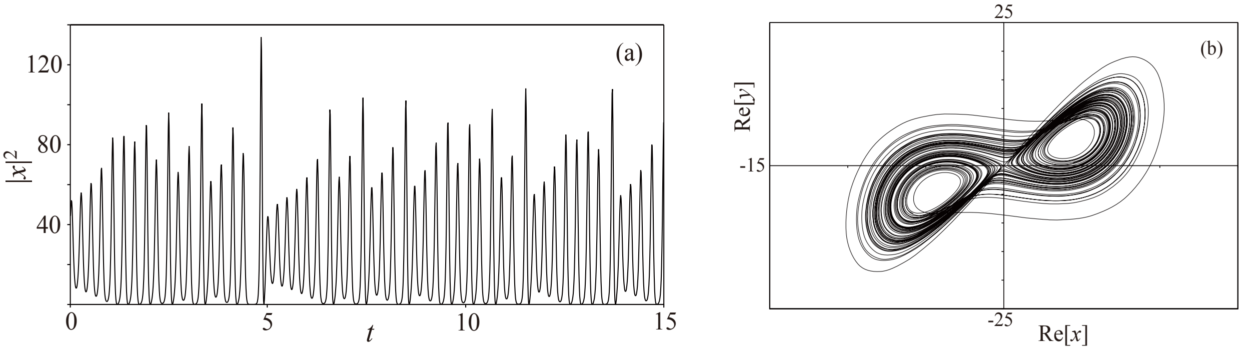

Figure 1. Laser chaos at $\delta = 0$, $\sigma = 3$, $r = 28$, $b = 1$. (a) laser output and (b) attractor.

categorized into class B lasers and they are stable in their solitary oscillations.

III. Chaos in Semiconductor Lasers

As discussed in the previous section, semiconductor lasers are stable lasers when there is no external perturbation. However, they are easily destabilized by external perturbations, since they are the introduction of extra degree of freedom to lasers. Self-optical feedback, optical injection, bias injection current modulation, and opto-electronic feedback are typical effects for external perturbations to semiconductor lasers [2]. Indeed, a perturbed laser shows chaotic oscillations. Taking an example of optical feedback in narrow-stripe edge-emitting semiconductor lasers, the laser equations, field E and carrier density n, are described by the following forms;

$$\frac{dE(t)}{dt} = \frac{1}{2}(1 - i\alpha)G_n\{n(t) - n_{th}\}E(t) + \kappa E(t-\tau)\exp(i\omega_0\tau) \tag{4}$$

$$\frac{dn(t)}{dt} = \frac{J}{ed} - \frac{n(t)}{\tau_s} - G_n\{n(t) - n_0\}\,|\,E(t)\,|^2 \tag{5}$$

where α is the linewidth enhancement factor, G_n is the optical gain, n_{th} is the carrier density at threshold, κ is the optical feedback coefficient, τ is the optical feedback time, ω_0 is the laser oscillation frequency, J is the injection current density, e is the elemental charge, d is the thickness of the laser cavity, τ_s is the carrier life time, and n_0 is the carrier density at transparency. The carrier density is equivalent to the population inversion in the previous section.

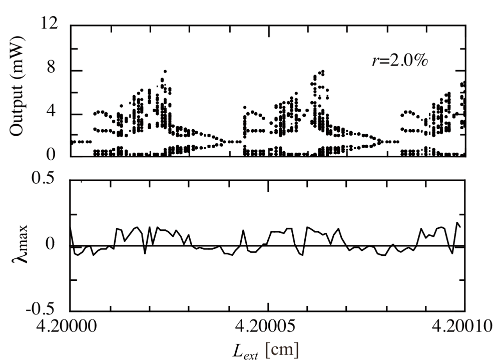

Figure 2. Chaotic bifurcation for a small change of external reflector. (a) Bifurcation diagram and (b) maximum Lyapunov exponent.

Depending on the parameters, we can observe a rich variety of chaotic oscillations due to the presence of the optical feedback terms (the final term in Eq.(4)). Instabilities and chaos in semiconductor lasers with optical feedback have also been demonstrated in experiments [2]. Figure 2 shows an example of a chaotic bifurcation diagram. Figure 2(a) is the bifurcation of the laser output power for a small change of the external cavity length (of the order of the wavelength) and Fig. 2(b) is the corresponding maximum Lyapunov exponent. From Fig. 2(b), the Lyapunov exponent has a positive value when the output becomes chaotic, while it is negative for a stable or fixed oscillation. Thus, irregular oscillations in semiconductor lasers subjected to optical feedback are proved to be chaos. In other schemes of external perturbations, a rich variety of chaotic oscillations are observed in semiconductor lasers [2].

IV. New Semiconductor Lasers; Instability and Control

Recently, many semiconductor lasers with various new structures have been developed to make them functional uses in applications. Examples are vertical-cavity surface-emitting lasers, broad-area semiconductor lasers, quantum-dot semiconductor lasers, and quantum-cascade semiconductor lasers. Those lasers are essentially unstable lasers even if they are operating at solitary oscillations. Also, instabilities are much enhanced by the introduction of external perturbations to those lasers [2].

Here, we show an example of chaos in broad-area semiconductor lasers and the method of control for the unstable oscillations. We do here not show the rate equations of broad-area semiconductor lasers. But, taking the spatial dependence along the wide active region of the laser cavity into consideration, we can formulate the rate equations suitable to broad-area semiconductor lasers. Then, the dynamics of broad-area semiconductor lasers are numerically analyzed. The typical feature of the dynamics is a filament phenomenon. Figure 3(a) shows an output power at the exit face of a broad-area semiconductor laser (time-resolved near-field pattern (NFP)). Bright spots of high intensities irregularly move as a zigzag manner, which looks like filaments. The spatial size of filaments is about several microns and the time size is about 10 ps. This irregular oscillation is proved to be chaos. As time-averaged beam intensity, the NFP is shown in Fig. 3(b), in which enhanced light outputs are observed at both edges. These enhanced peaks are typical features in real broad-area semiconductor lasers.

The quality of the laser beam in broad-area semiconductor lasers is rather poor for applications, therefore, the control of the beam quality is expected. The beam quality may be improved by the device design, however, it is difficult to improve it only by device design, since we cannot eliminate the diffraction effects of light and the carrier diffusion along the stripe width of the laser device. The beam quality can be controlled by optical feedback and optical injection techniques. Figure 4(a) shows a numerical example. In this case, the laser is optically injected from a different laser and the filament oscillation observed in a solitary laser like Fig. 3(a) is almost eliminated. The corresponding time-averaged NFP in Fig. 3(b) shows a flat-top beam profile. Then, we obtain an excellent diffraction-limited beam profile at the far-field in the broad-area semiconductor laser, which is suitable for applications.

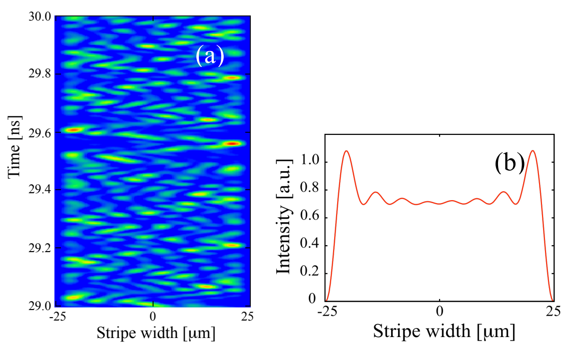

Figure 3. Filament oscillations in broad-area semiconductor laser. (a) Time-resolved NFP and (b) time-averaged NFP.

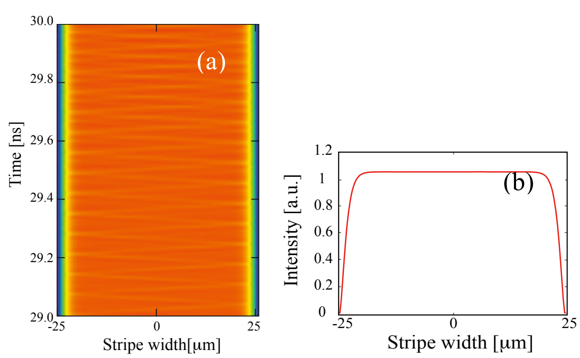

Figure 4. Controlled filaments by strong optical injection. (a) Time-resolved NFP and (b) time-averaged NFP.

V. Applications of Chaos in Semiconductor Lasers

Breakthroughs for applications of chaos were made in the early 1990s [2]. The ideas of chaos control and chaos synchronization were proposed and developed in this decade as common interests in various fields of nonlinear and chaos research. Also, fixed point or periodic oscillations, precursor to the onset of chaos in semiconductor lasers with optical feedback, can be used for laser control and optical measurements. The possibility of chaotic communications has been discussed based on chaos synchronization in two semiconductor laser systems. As related topic to secure communications, irregular chaotic oscillations in semiconductor lasers have also provided a new method of ultrafast physical random number generations, which is the key technology in modern cryptographic applications [6]. Also for those applications, photonic integrated circuits to generate chaotic light have been proposed [2].

As a promising technique of secure communications based on chaotic systems, we briefly discuss chaos communications using semiconductor lasers. We prepare two similar chaotic lasers for the transmitter and receiver lasers. An example of chaotic lasers is a semiconductor laser with optical feedback as discussed in section 3. A chaotic signal generated in the transmitter together with a small message to be embedded is sent to the receiver laser. In the receiver, only the chaotic signal is reproduced due to the chaos-pass filtering effect. Then, subtracting the reproduced chaotic signal from the transmission signal, the message is successfully extracted. The message is small enough to conceal it into chaotic irregular signal and the keys of device parameters and operating conditions of the two systems can guarantee the security of the systems. The key technology of chaos communications is chaos synchronization between the transmitter and receiver lasers. Figure 5 shows an experimental example of chaos synchronization between two semiconductor lasers with optical feedback. Note that it is not self-evident that we could expect the same synchronous outputs in two nonlinear systems, since chaos is sensitive to initial conditions of the systems and we could not expect the same waveforms when the two systems are isolated.

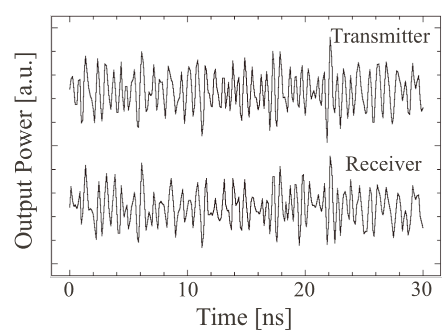

Figure 5. Chaos synchronization in semiconductor lasers with optical feedback. Transmitter chaos (upper trace) and receiver chaos (lower trace).

VI. CONCLUSIONS

Chaos in semiconductor lasers is of particular importance in practical applications, since chaos induced by semiconductor lasers is very fast and the main frequency of irregular oscillations is usually over giga hertz, which is much faster than those of chaos such as in electronic circuits. Also, light is a carrier of modern communications and such chaotic oscillations match well with fast data transmissions in the existing optical network channels. Applications of chaotic lasers are still growing and developing. Thus, chaotic lasers are not only important for basic research but also for engineering applications.

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