Dynamics in a Compound Cavity Semiconductor Laser Induced by Small External-Cavity-Length Change

Yutaka Ikuma and Junji Ohtsubo, *Member, IEEE*

Abstract—For the short-range variations of the external cavity length, the dynamic behaviors of a semiconductor laser with optical feedback are investigated by the numerical simulations and experiments. Under the condition of a single-mode oscillation, the laser output power shows periodic undulation along the external cavity length whose period is equal to half of the optical wavelength. At weak to moderate external optical feedback, stable, periodic, quasi-periodic, and chaotic oscillations of the laser output power are observed within the periodic undulation. Experimental results of periodic and quasi-periodic oscillations obtained by the laser output power and the optical spectrum support the predictions from the numerical analysis based on the rate equations.

Index Terms—Chaos, optical feedback, semiconductor laser.

I. INTRODUCTION

THE characteristics of a semiconductor laser with optical feedback have interested many investigators since it is an excellent model for nonlinear optical systems and includes a rich variety of nonlinear dynamics. When the light reflected from an external reflector couples with the original field in the laser cavity, the laser oscillation is affected considerably [1], [2]. At weak to moderate optical feedback which is very important in actual applications of a semiconductor laser, the output power of the compound cavity semiconductor laser shows interesting dynamical behaviors such as stable state, periodic and quasi-periodic oscillations, and chaos with the change of the system parameter values. The dynamic behaviors of a semiconductor laser with optical feedback are mainly influenced by three parameters in the system, which include the reflectivity of the external mirror, the length of the external cavity, and the injection current [3]. There exist many theoretical studies for the dynamics of a semiconductor laser with optical feedback, but only a few experimental studies have been done for the nonlinear system. In the theoretical studies, several assumptions have been made to enhance the expected dynamics. Therefore, the experimental studies for the dynamic behaviors of the nonlinear system are expected.

The characteristics of the laser oscillation both for short- and long-range variations of the external cavity have been reported in several papers [4]–[14]. Here, short range means

the change of the external cavity length compatible with the optical wavelength, while long range denotes the variations of it more than the effective internal cavity length of the semiconductor laser (usually millimeters or more). Though there exist many theoretical and experimental studies for the dynamics of the long-range variations of the external cavity [4]–[9], only a few studies have been done for the dynamics of short-range variations [10]–[14]. The well-known feature of the dynamics of the short-range variations is the periodic undulation of the laser output power with a period equal to half of the optical wavelength due to the external mode hopping. The key to the dynamics is the relaxation oscillation of the laser which remains undamped due to the effect of the external optical feedback. It has been proved that not only the frequency corresponding to the external cavity length but also the relaxation oscillation frequency plays an important role for the dynamic behaviors of the output power in a semiconductor laser with optical feedback [6]–[9]. With nonvanishing relaxation oscillation, the laser output power behaves like periodic oscillation and evolves into quasi-periodic and, finally, chaotic oscillations with the increase of the feedback level, and these phenomena have been reported for the long-range variations. The similar bifurcations are expected to be observed for the short-range variations of the external cavity length.

In this paper, we investigate the dynamic characteristics of a semiconductor laser with optical feedback by the numerical simulations based on the rate equations when the external cavity length has a slight change compatible with the optical wavelength of the laser oscillation. Here, we limit the phenomena for a single laser mode oscillation, i.e., the laser output does not hop around among the internal cavity modes even in the presence of the external optical feedback. It is well known that the laser output power shows undulation with a period equal to half of the optical wavelength when external optical feedback exists in the semiconductor laser. But, by the numerical simulations, we for the first time observed steady-state, periodic, quasi-periodic, and chaotic oscillations within each period of the undulation. For short-range variations of the external cavity length, the route to chaos induced by the interaction between the relaxation oscillation of the semiconductor laser and the external cavity mode was demonstrated. The experiments are also conducted and the obtained results are comparable with the numerical simulations.

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The authors are with the Faculty of Engineering, Shizuoka University, Hamamatsu, 432 Japan.

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II. THEORETICAL BACKGROUND

The theoretical study of the dynamic characteristics of a semiconductor laser with optical feedback has been performed by many researchers. For the dynamics of short-range variations of the external cavity (compatible with optical wavelength), the same laser rate equations as for the previous studies can be used. We here briefly summarize the theoretical background for the nonlinear system. The dynamics of semiconductor laser with optical feedback is described by the rate equations modeled by Lang and Kobayashi [1]. Assuming that the laser oscillates in a single longitudinal mode with an angular frequency ω_0 , the complex electric field in the active region is written as $E(t)\exp[i(\omega_0 t + \phi(t))]$, where $\phi(t)$ is the phase change due to the feedback effect. Then, the rate equations for the amplitude and phase of the complex electric field and the carrier density are given by

$$\frac{dE(t)}{dt} = \frac{1}{2} \left\{ g(N(t) - N_0) - \frac{1}{\tau_p} \right\} E(t) + \frac{\kappa}{\tau_{\text{in}}} E(t - \tau) \cos \theta(t) \quad (1)$$

$$\frac{d\phi(t)}{dt} = \frac{\alpha}{2} \left\{ g(N(t) - N_0) - \frac{1}{\tau_p} \right\} - \frac{\kappa}{\tau_{\text{in}}} \frac{E(t - \tau)}{E(t)} \sin \theta(t) \quad (2)$$

$$\frac{dN(t)}{dt} = J - \frac{N(t)}{\tau_s} - g\{N(t) - N_0\}|E(t)|^2 \quad (3)$$

where g is the linear gain coefficient, N_0 is the carrier density at transparency, α is the linewidth enhancement factor, J is the injection current density, τ_p is the photon lifetime, τ_s is the carrier life time, $\tau = 2L/c$ is the external cavity round-trip time where L is the distance from the laser facet to the external reflector and c is the light velocity in vacuum, and $\tau_{\text{in}} = 2\eta l/c$ is the round-trip time within the laser cavity where l is the internal cavity length and η is the refractive index of the laser cavity. In our case, the external cavity length L is varied for a small distance compatible with the optical wavelength up to about 1 μm . In the numerical simulations, the Langevin noise terms are also neglected since we are concerned about the pure dynamics of the nonlinear system. $\theta(t)$ represents the phase coupling between the original light in the cavity and the delayed light from the external reflector and is given by the following forms:

$$\theta(t) = \omega_0 \tau + \phi(t) - \phi(t - \tau). \quad (4)$$

The feedback parameter κ is written by

$$\kappa = (1 - r_0^2) \frac{r}{r_0} \quad (5)$$

where r_0 and r are the amplitude reflectivities of the laser exit face and the external reflector, respectively. We assume the same reflectivities for the front and back facets of the laser cavity and this is true for a laser used in our experiments. Since multiple reflections between the laser facet and the external reflector are neglected, Equations (1)–(3) are valid for a weak to moderate feedback level. The relation between

the angular frequency of the laser oscillation ω_s and the steady state solitary laser angular oscillation ω_0 is given by

$$\omega_0 = \omega_s + C \sin(\omega_s + \arctan \alpha) \quad (6)$$

with

$$C = \frac{\kappa}{\tau_{\text{in}}} \sqrt{1 + \alpha^2}. \quad (7)$$

Depending on the value of the important parameter C , the laser oscillation frequency ω_s has single or multiple solutions. We here choose an angular frequency of the maximum gain as a steady-state solution. The steady-state solution ω_s changes as the variations of the external cavity length (here, we are interested in a small external cavity length change) and this induces external mode hopping of the laser output. For short range variations of the external cavity length, the behaviors of the laser output power is not so simple and it shows stable, periodic, and, sometimes, chaotic oscillations. In the following, we demonstrate some dynamic characteristics of the laser output power for the variations of the external cavity length by the numerical simulations based on the rate equations and, then, the experimental results are also given.

III. SIMULATION RESULTS

We numerically calculate (1)–(3) by employing the fourth-order Runge–Kutta algorithm for the variations of the external cavity length. The parameter values for the semiconductor laser with the oscillation wavelength of $\lambda = 780$ nm used in the simulations are the same as those in the previous paper [3] and the values are compatible with those used in the following experiments. Fig. 1 shows some examples of the laser output power for the external cavity length from 4.2000 to 4.2001 cm (the change of the cavity length ΔL is 1 μm) at the injection current $J = 1.3J_{\text{th}}$ (J_{th} is the injection current at threshold). The laser output power shows undulation for the variations of the external cavity length and the amplitude of the undulation increases with the increase of the external reflectivity. The period of the undulation is equal to half of the wavelength of the laser oscillation. For a small external reflectivity in Fig. 1(a), the laser output power changes continuously with a small amplitude. On the other hand, it suddenly jumps at every interval of the half-wavelength, as shown in Fig. 1(b)–(d). The frequency of the internal laser cavity mode is fixed as $\Delta f_{\text{in}} = c/2\eta l$, while the frequency $\Delta f_{\text{ext}} = c/2L$ of the external cavity mode changes with the variations of the external cavity length. The jump of the laser output power shown in the figure is caused by a mode hop between successive external cavity modes. The increase of the optical feedback level gives raise to the influence on the external cavity mode hoppings and the oscillation mode hops by selecting one of external cavity modes for the variations of the external cavity length. It is noted that the phases (namely, the jump point of the laser output power) are different from each other, though the periods remain unchanged. For a single-mode laser oscillation, undulation of the period equal to half of the wavelength has already been reported in several papers. But, in weak to moderate feedback regimes, the phenomena are not so simple as shown in Fig. 1 (b)–(d). Namely, within

Fig. 1. Numerical results of the laser output power for the variations of the external cavity length at $J/J_{th} = 1.3$ and different external reflectivities.

each period of the undulation, the laser output power shows irregular fluctuations. As will be shown later, the chaotic behaviors of the laser output power are observed just after the external mode jumps and the onset of chaos strongly depends upon the external reflectivity. The chaotic behaviors within the period of the undulation have never been reported or observed to date.

In Fig. 2, we show optical spectra for the variations of the external cavity length to confirm the mode hoppings observed in Fig. 1. The origin of the horizontal axis in the figure is the frequency of the solitary laser ω_0 . In the presence of the optical feedback, the oscillation frequency deviates from that of the solitary laser. Fig. 2(a) is the optical spectrum corresponding to Fig. 1(a). The optical spectrum is exactly a single mode and its frequency deviates continuously for the variations of the external cavity length with the period of half of the optical wavelength. Fig. 2(b) is also the optical spectrum corresponding to Fig. 1(d). For large optical feedback, the

optical spectrum behaves completely different from that for a small optical feedback. Before the mode jump at $L = 4.2000$ cm [optical spectrum in the bottom of Fig. 2(b)], the spectrum is almost single and the laser stays stable. However, as shown in the second spectrum from the bottom at $L = 4.2000$ cm + $0.05 \mu\text{m}$, the spectrum is completely destroyed and the main peak shifts right (though it is not clear in the figure). The jump of the frequency is 3.54 GHz which is nearly equal to the frequency of the external cavity length. The accompanying modes in this spectrum include the external mode and relaxation oscillation frequencies, though the spectra are not clearly observed. The state corresponds to chaos of the laser output power and also the coherence collapse state. With a further increase of the external cavity length, the optical spectrum remains in the chaotic state and the main peak of the spectrum shifts for a lower frequency. At the external cavity length of $L = 4.2000$ cm + $0.3 \mu\text{m}$ (the seventh spectrum from the bottom), the sharp main peak recovers in its optical spectrum and subpeaks corresponding to the relaxation oscillation are clearly visible. This state corresponds to a periodic oscillation induced by the relaxation oscillation as is frequently observed in the laser output power with optical feedback [7]. With further increase of the external cavity length, the laser output recovers a single mode. The same procedure is repeated for every external cavity length with the period of half of the optical wavelength.

Finally, we investigated bifurcation diagrams of the laser output power for the variations of the external cavity length. Fig. 3 shows the bifurcation diagram for a small external feedback corresponding to Fig. 1(a). In actuality, the laser output power does not bifurcate in this case and it stays stable, though it has a small undulation with the period of half of the optical wavelength. The maximum Lyapunov exponent is also calculated for Fig. 3, but its value is usually less than zero and it occasionally takes very small positive values. Therefore, the laser output power stays stable. Fig. 4 shows the bifurcation diagram and the maximum Lyapunov exponent λ_{max} corresponding to Fig. 1(d). At the external cavity length around 4.2000 cm, the laser output power is stable and it is almost single mode oscillation. As the increase of the external cavity length in Fig. 4(a), it suddenly becomes unstable and shows chaotic behaviors. Further increase of the external cavity length, it reduces to quasi-periodic to periodic oscillations and finally to stable state. This process repeats for the increase of the external cavity length and the period is equal to the half of the optical wavelength. To help understanding the dynamic behaviors of the laser output power, the maximum Lyapunov exponent is calculated from the obtained time series of waveforms and shown in Fig. 4(b). The maximum Lyapunov exponent has a positive value in chaotic regions in Fig. 4(a), while it has zero or negative value in periodic and stable states. Thus, it is concluded that the irregular laser output power is induced by chaos in the nonlinear system and periodic and chaotic bifurcations are produced by the small change of the external cavity length. From the result of this figure together with that of Fig. 3, the external mode hop due to the external cavity length change induces chaotic bifurcations and not only the external cavity

Fig. 2. Variations of the optical spectrum for the external cavity length change corresponding to Fig. 1. (a) $r = 0.1\%$. (b) $r = 7.0\%$.

Fig. 3. Bifurcation diagram of the laser output power corresponding to Fig. 1(a).

length but also the relaxation oscillation of the laser play important roles in the dynamic behaviors.

IV. EXPERIMENTS AND RESULTS

The experimental setup is shown in Fig. 5. The semiconductor laser used is a single-mode CSP laser diode (Hitachi HL7801E), which oscillated at a single wavelength of 780 nm and a maximum power of 5 mW. The injection current to the semiconductor laser is supplied by the stabilized current drive circuit. The threshold current of the laser was 50.0 mA and the bias injection current was fixed as 65.0 mA ($J/J_{th} =$

Fig. 4. Bifurcation diagram of the laser output power and the maximum Lyapunov exponent corresponding to Fig. 1(d).

1.3) throughout the experiments. The temperature of the laser was stabilized by an automatic temperature control circuit

Fig. 5. Schematic diagram of experimental setup. LD: laser diode; PD: photodiode; BS: beamsplitter; v-ND: variable neutral density filter; PZT: piezo translator.

Fig. 6. Dependence of the laser output power for the long range variations of the external cavity. External reflectivity is $R = 2.0\%$ and injection current is $J = 1.3J_{th}$.

within the accuracy of $\pm 0.01^\circ\text{C}$. The emitted light from the laser diode (LD) was collimated by a Lens and split by a beamsplitter (BS). One of the beams was reflected by an external mirror through a variable neutral density filter (v-ND) and fed back to the laser cavity. For the short-range variations of the external cavity, the mirror is mounted on a piezo translator (PZT) and the external cavity length can be varied up to several micrometers by changing the applied voltage. The long-range variations of the external cavity are also possible by a motor-driven moving stage controlled by a microcomputer on which the mirror together with the PZT is mounted. The other beam was fed to a Fabry-Perot interferometer (free spectral range of 7.5 GHz) to observe optical spectrum change. The laser output power was also monitored by a photodiode (PD) installed within the LD package.

In the theoretical analysis, we assumed a single-mode operation for the semiconductor laser oscillation. But, in the actual experiment, when the external optical feedback exists, the switching among internal modes or two-mode competition occurs depending on the external feedback level and the external cavity length [4], [5]. In that case, we must consider two modes or a multimode model for a semiconductor laser with optical feedback. However, there exists a state of a single-mode operation even if optical feedback presents. Fig. 6 shows

Fig. 7. Laser output power (lower trace) as a function of the short-range variations of the external cavity near the dip m_2 observed in Fig. 6. Upper trace of a triangular signal is the applied voltage to the PZT. External reflectivity is $R = 2.0\%$ and injection current is $J = 1.3J_{th}$.

the output power dependence on the long-range variations of the external cavity. Dips are observed periodically, whose period is equal to the effective internal cavity length ηl [4], [5]. The period between the adjacent dips is 1.0 mm and this value is consistent with the estimated value of ηl . At the locations of dips and around there, the laser operates always single mode, while the internal mode becomes unstable for the other external cavity length and internal mode switching or two-mode competition are observed. Therefore, we choose a location at or around dips as an observation point to investigate the dynamic behaviors and chaotic bifurcations under a single-mode condition. Then, the external mirror is moved on or near one of the dips by the motor driven stage and, there, a small deviation driven by the PZT is applied to the external mirror. In the following experiments, the external cavity length is set to 4.2 cm which corresponds to the dip marked m_2 in the figure. The value of 4.2 cm is for the free space length and the actual optical path length is different from this value since the lens, the beamsplitter, and the variable neutral density filter are inserted along the optical path. The external reflectivity is measured to be $R = 2.0\%$ and the same reflectivity is used throughout the experiments. The external reflectivity in the experiments is the intensity reflection and its value is not exactly the same as that used in the previous simulations. Furthermore, the amplitude reflectivity is usually used in the theoretical calculation instead of the intensity reflectivity. The reflectivity employed in this experiment is the reflection fraction of the returned light intensity to the intensity emitted from the lens in front of the laser diode facet. It is not exactly the fraction of the intensity or amplitude fed back into the active region in the semiconductor laser. The estimated fraction of the intensity actually returned into the active region is about several tenths to one-hundredth of the experimental ratio [4].

Fig. 7 shows an example of the waveforms of the laser output power due to the variations of the external cavity length. The upper trace of a triangular signal in the figure is the applied voltage for the PZT which corresponds to the small displacement of the external mirror. The lower trace is the waveform of the laser output power. As is already discussed in the simulations, the undulation of the output power has the period of half of the optical wavelength. It is noted here that

Fig. 8. Optical spectra (left) for the variations of the external cavity length corresponding to Fig. 7. Offset of the external cavity length is 4.2 cm and external reflectivity is also $R = 2.0\%$ and injection current is $J = 1.3J_{th}$.

the period of $\lambda/2$ is only observed for a single-mode operation of the laser, and the period of undulation becomes $\lambda/4$, $\lambda/6$, or $\lambda/2m$ (m being an integer) when the internal mode switching, or two- or multimode competition occurs.

Fig. 8 shows optical spectra for the variations of the external cavity length corresponding to Fig. 7. The stable laser output power, for example, at $\Delta L = 0.939 \mu\text{m}$ (the second spectrum from the top) switches the state to unstable one at $\Delta L = 1 \mu\text{m}$ which includes the frequencies of the external cavity length and the relaxation oscillation, though the frequencies corresponding to the relaxation oscillation and the external cavity length are not distinct. The relaxation oscillation frequency can be obtained from period-1 oscillations such as the third and fourth spectra from the top to be 2.81 GHz and the external mode frequency is calculated to be 3.57 GHz from the external cavity length of 4.2 cm (actually, the effective cavity length is slightly larger than this length as already mentioned). In the top spectrum, we can observe twin spectra whose separation is about 700 MHz. This frequency is consistent with that calculated from an interaction between the relaxation oscillation and the external cavity mode. The state can be considered as a quasi-periodic or weak chaotic oscillation of the laser output power. The process during which the laser output power evolves from unstable to quasi-periodic oscillations and finally to stable oscillation for the increase of the external cavity length is very consistent with the numerical calculation. The period of the jump along the external cavity

length is equal to half of the optical wavelength and the result is also consistent with the simulation result.

V. CONCLUSION

We have demonstrated chaotic dynamics of a semiconductor laser with optical feedback when the external cavity length has small variations compatible with the optical wavelength. The laser output power and the optical spectrum have been investigated for the variations of the external cavity length. Under the condition of a single-mode oscillation, the laser output power shows periodic undulation with the period of half of the optical wavelength for the change of the external cavity length. At weak to moderate external optical feedback, stable, periodic, quasi-periodic, and chaotic oscillations of the laser output power are observed within the periodic undulation. This is the first observation of the chaotic behaviors of semiconductor laser with optical feedback for the short-range variations of the external cavity. We have also done numerical simulations for this model based on the rate equations. Experimental results are in excellent agreement with the predictions from theoretical analysis.

There exist a lot of theoretical studies for the dynamic behaviors of semiconductor lasers with optical feedback, however, little has been done for the experimental research. One of the reasons is that the phenomena include very high frequency oscillations more than gigahertz and it is very difficult to observe such a high-frequency waveform directly. But the chaotic aspects can be investigated from rather static physical quantities such as the low-frequency laser output power and the optical spectrum as is done in this study. Experimental studies are now a very important issue for the dynamics of a semiconductor laser with optical feedback.

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Yutaka Ikuma was born in Shizuoka, Japan, in 1971. He received the B.S. degree in optoelectronics and mechanical engineering from Shizuoka University in 1996. He is currently working towards the M.S. degree at the same university.

His research interest is nonlinear dynamics in semiconductor lasers with optical feedback.

Mr. Ikuma is a member of the Japanese Society of Applied Physics.

Junji Ohtsubo (M'95) received the B.S. degree in electronics from the Kyushu Institute of Technology in 1973 and the M.S. and Ph.D. degrees in electronics from Hokkaido University in 1975 and 1978, respectively.

In 1978, he joined the Mechanical Engineering Laboratory. During 1981–1982, he was a Research Associate at the Institute of Optics, University of Rochester, Rochester, NY. He joined Shizuoka University, Hamamatsu, Japan, as an Associate Professor in 1985 and is presently a Professor. His current research interests are statistical optics, speckle, optical metrology, active interferometry, optical information processing and computing, and nonlinear dynamics in optics.

Prof. Ohtsubo is a member of the Optical Society of America, SPIE, the Japanese Society of Applied Physics, the Optical Society of Japan, and the Laser Society of Japan.