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Experimental Investigation of Stability Enhancement in Semiconductor Lasers with Optical Feedback

Shu-Ying YE[1] and Junji OHTSUBO[2,*]

[1]*Graduate School of Electronic Science and Technology,* [2]*Faculty of Engineering, Shizuoka University, 3-5-1, Johoku, Hamamatsu, 432-8561 Japan*

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The stability enhancement of laser output power for the change of external cavity position in semiconductor lasers with optical feedback is observed by experiment. The relaxation oscillation frequency which plays an important role in the dynamics of the nonlinear system is also investigated as a function of the external cavity length. The period of the stability enhancement along the position of the external cavity is exactly coincident with the length corresponding to the relaxation oscillation frequency of the solitary laser. The experimental results are compared with theoretical and excellent coincidence between the two is found.

Key words : semiconductor laser, optical feedback, chaos, relaxation oscillation, linear stability analysis

1. Introduction

Semiconductor lasers with optical feedback have drawn attention as one of the most interesting nonlinear systems to generate optical chaos.[1-15] When the light reflected from an external reflector couples into the laser cavity, the laser output is considerably affected. The output power of the compound cavity semiconductor laser shows a rich variety of dynamical behaviors such as stable state, periodic and quasi-periodic oscillations, and chaos with variations of the parameters which include the reflectivity of the external mirror, the length of the external cavity, and the injection current. The key to the chaos dynamics is the relaxation oscillation of the laser which remains undamped due to the effect of the external optical feedback.[2-4] With non-vanishing relaxation oscillation, the laser output behaves like periodic oscillations and evolves into quasi-periodic and, finally, chaotic oscillations with increase of the feedback level.[5-7]

It has been proved that not only the external cavity mode but also the relaxation oscillation plays an important role in the stability and instability of the output power in a semiconductor laser with optical feedback.[8-13] The stability and instability of the nonlinear system are important issues from the viewpoint of both physical aspects and application. In the applications of chaos in the external-cavity semiconductor laser, the chaos control algorithm can be used effectively to suppress the noise which is caused by the optical feedback.[14,15] There exist many theoretical reports on the dynamics, stability, and instability of semiconductor lasers with optical feedback, but only a few experimental studies have been done on the nonlinear system. In former theoretical studies, assumptions were made to enhance the expected dynamics and the Langevin noises were often neglected. Experimental studies on the dynamics of the nonlinear system have thus been anticipated.

We discuss here the stability enhancement of the laser output power for change of the external cavity position by experiment. We here to the stable state as a state of fixed or constant laser output power. The periodic enhancement of the stability for variations of the external cavity position obtained in the theoretical studies is confirmed by the experiment. The relaxation oscillation frequency of the semiconductor laser is important for the stability and instability of the laser output power, so it was also experimentally investigated. It was verified that the period of stability peaks along the external cavity length was exactly equal to the length corresponding to the relaxation oscillation frequency of the solitary laser. The obtained results are well coincident with the theoretical expectations, although the theory usually includes many assumptions and sometimes neglects the Langevin noise terms.

2. Theoretical Background

The dynamic characteristics of semiconductor lasers with optical feedback has been theoretical studied by many researchers using numerical simulations from the rate equations, and the stability of the system has also been studied based on the linear stability analysis of the rate equations. We here briefly describe the previous theoretical results of the stability for a nonlinear system used in later experiments. The dynamics of semiconductor lasers 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 of the field. Then, the rate equations for the amplitude and phase of the complex electric field and the carrier density are given by

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

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

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

*E-mail: ohtsubo@eng.shizuoka.ac.jp

where g is the linear gain coefficient, N_0 is the carrier density at transparency, α is the linewidth enhancement factor, and J is the injection current density. τ_p is the photon life-time, 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 $\tau_{in}=2\eta l/c$ 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. $\theta(t)$ 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 form

$$\theta(t)=\omega_0\tau+\phi(t)-\phi(t-\tau)\,. \tag{4}$$

The feedback parameter κ is written by $\kappa=(1-r_0^2)r/r_0$, where r_0 and r are the amplitude reflectivities of the laser exit facet and the external reflector, respectively. Since multiple reflections between the laser facet and the external reflector are neglected, Eqs. (1)-(4) are valid for a weak to moderate feedback level.

The laser output power calculated by Eqs. (1)-(4) is stable under certain parameter conditions, however, it becomes unstable for other parameter regions. The variable parameters which determine the stability and instability in the system are the injection current J, the external reflectivity r, and the external cavity length L. By applying the linear stability analysis for the rate equations with reasonable assumptions,[8,12] the condition yielding the limit of stable laser oscillation is given by

$$\Omega^2-\omega_R^2=\frac{\Omega}{\tau_R}\cot\left(\frac{\Omega\tau}{2}\right), \tag{5}$$

where ω_R $(=2\pi f_R)$ is the relaxation oscillation angular frequency of the solitary laser and $\tau_R^{-1}=\tau_s^{-1}+gE_s^2$ (E_s is the steady state solution for the field amplitude). The relaxation oscillation frequency of the solitary laser is given by

$$f_R=\frac{1}{2\pi}\sqrt{\frac{gE_s^2}{\tau_p}}\,. \tag{6}$$

At the relaxation oscillation frequency $\Omega=\omega_R$, periodic solutions for the time delay τ (equivalently periodic solutions for the external cavity length as $L=mc/2f_R$, m being an integer number) are obtained as the stable condition from Eq. (5). In actual laser systems, the "stable" laser output power more or less fluctuates at the relaxation frequency f_R with negligible amplitude not only due to the Langevin noises but also due to the presence of external optical feedback. When the external optical feedback exists, a certain linear mode derived from the linear stability analysis is always excited as an accompanying mode with the laser relaxation oscillation, and it becomes the highest mode[14] (here, "highest" means that the real part of the linear mode has the highest value among linear modes). We refer to this mode as the relaxation oscillation mode in the presence of optical feedback. With the increase of external feedback reflection, this mode is initially excited as an unstable oscillation mode of the laser output power. The relaxation oscillation frequency (or strictly speaking, the excited frequency near the relaxation oscillation of the solitary laser) also varies depending on the values of the system parameters J and L.

At fixed external cavity length and injection current, the laser output power evolves from a fixed state (which we refer to as a stable state) into periodic states, and, finally, into chaotic states with the increase of the external reflectivity. The relaxation oscillation frequency has an important function in the dynamics of the semiconductor laser with optical feedback on the route to chaos via periodic bifurcation, and the dominant frequency of the period-1 oscillation is the relaxation oscillation frequency of the laser. The periodic structure of the stability along the external cavity position at a fixed injection current is calculated from the rate equations.[12] Figure 1 shows the boundary between the stable state and the period-1 oscillation for the external reflectivity at the injection current of $J=1.5J_{th}$. The parameter values used in the calculation are the same as those in Ref. 12) and are compatible with those in the following experiments. The periodic enhancement of the stability is easily observed from the figure. The period is $D=4.64$ cm and the corresponding frequency is calculated to be $f_p=c/2D=3.23$ GHz which is exactly equal to the relaxation oscillation frequency for the solitary laser. Figure 2 shows the relaxation oscillation frequency for variations of the external cavity length calculated from

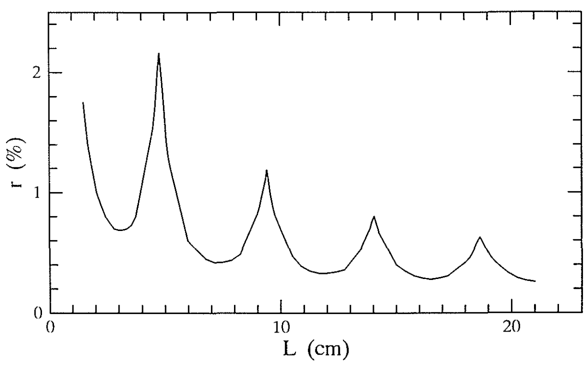

Fig. 1. Calculated critical reflectivity of the stable state at $J=1.5J_{th}$.

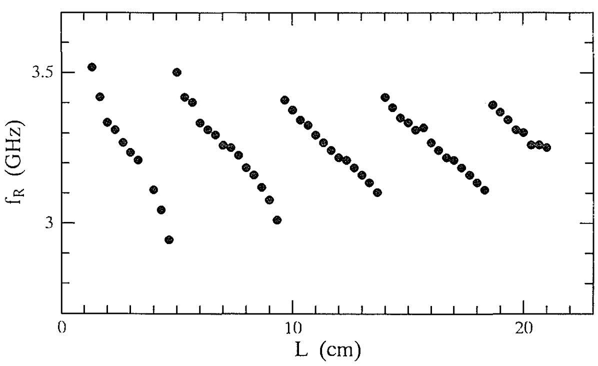

Fig. 2. Relaxation oscillation frequency as a function of the external cavity length $J=1.5J_{th}$.

the linear stability analysis for the rate equations under the same conditions as in Fig. 1. The relaxation oscillation frequency decreases with increase of the external cavity length, jumps up at the stability peaks (see Fig. 1), and then repeats the same process for the increased external cavity length. The period of the jumps is equal to that obtained in Fig. 1. In the following experiments, we demonstrate these stability enhancements and the variations in the relaxation oscillation frequency along the external cavity length.

3. Experiments and Results

The experimental setup is shown in Fig. 3. The semiconductor laser used was a single mode channeld substrate plannar (CSP) laser diode (Hitachi HL7801E), which oscillated at a single wavelength of 780 nm and a maximum power of 5 mW. We used it because the laser was sensitive to optical feedback and the dynamic behaviors which we were interested in could easily be observed. The injection current to the semiconductor laser was supplied by a stabilized current drive circuit (CDC). The threshold current of the laser was 46.5 mA and the temperature was stabilized by an automatic temperature control (ATC) circuit within an accuracy of ±0.01°C. The light emitted 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 (M) through a variable attenuator (VA) and fed back to the laser cavity. The other beam was fed to a Fabry-Perot interferometer (free spectral range of 10 GHz) to observe optical spectrum change. The laser output power was also monitored by a photodiode (PD) installed within the laser diode package.

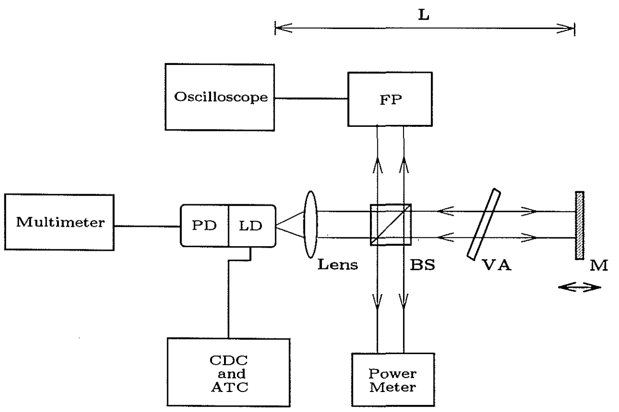

Fig. 3. Experimental setup. LD: laser diode, PD: photodiode installed in the LD package, BS: beamsplitter, VA: variable attenuator, M: external mirror, FP: Fabry-Perot interferometer.

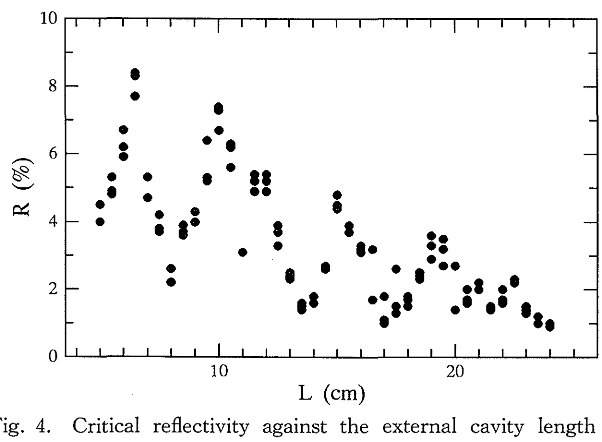

Fig. 4. Critical reflectivity against the external cavity length at which the laser output power evolves into periodic oscillation from the stable state. The injection current is 69.7 mA (J/J_{th}=1.5).

Figure 4 shows the critical reflectivity (intensity reflectivity) with the variations of the external cavity length at which the laser output power evolves from stable state to periodic state. The onset of period doubling bifurcations is determined by the optical spectrum from the Fabry-Perot interferometer. When the laser output becomes unstable, a subpeak corresponding to the relaxation oscillation frequency appears in the optical spectrum. We defined the critical reflectivity of the boundary between the stable state and period-1 oscillation at which the subpeak of the optical spectrum grows up to about 1% of the main laser oscillation peak. The intensity reflection referred to here was calculated from the fraction of the reflectivity through the optical components, and the diffraction loss coupled with the objective lens in front of the laser facet is not included. Taking the diffraction effect into consideration, the fraction of the intensity fed back to the active region is estimated as about one-hundredth of the above reflectivity, which is roughly compatible with the simulation results.[16] We can see the periodic structure of the stability enhancement in the figure. However, between the ranges of the external mirror length L=9 and L=13 cm, peak positions and periodicity are not clearly visible and the detected peak positions do not seem to be coincident with the positions for the frequency jumps of the relaxation oscillation in the following experiment. In the experiments, we carefully choose the condition of the injection current and the temperature without internal laser mode hopping, but internal mode hopping also depends on the external reflectivity and the external cavity length. The determination of the boundary in the experiment is very critical and the spectrum peaks fluctuate unstably in these regions. We did not observe internal mode hopping throughout this experiment, but one possible reason for this disagreement may be unstable laser oscillation due to the internal mode competition. A rough estimate of the average length of the period is 3.2 cm, which corresponds to the frequency of 4.69 GHz. The injection current to the laser diode is 69.7 mA (J/J_{th}=1.5) and the corresponding relaxation oscillation frequency of the solitary laser is about 4.5 GHz. The experimental result coincides well with the simulation in Fig. 1.

Figure 5 shows the variations of the relaxation oscillation frequency against the external cavity length at the onset of periodic oscillation. The injection current is fixed to be 69.7 mA. The periodic structure is also seen in the figure and the period is almost the same as that of the previous figure. Frequency jumps occur at enhanced sta-

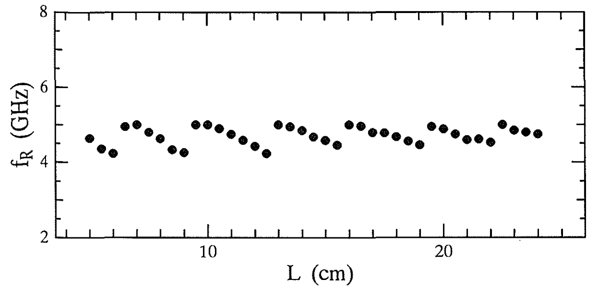

Fig. 5. Variations of the relaxation oscillation frequency against the external cavity length. The injection current is 69.7 mA.

bility peaks corresponding to Fig. 4, and then the frequency decreases with the increase of the external cavity length. Again, the frequency jump is observed repeatedly in every external cavity separation corresponding to the relaxation oscillation frequency of the solitary laser. However, as mentioned in Fig. 4, poor coincidence between the jumping positions at L=9.5 and L=13 cm with the spectral peak positions in Fig. 4 is found. The comparison between the experimental result obtained in Fig. 5 and theoretical one in Fig. 2 shows excellent coincidence.

Figure 6 shows optical spectra observed at a fixed external cavity position. The injection current is 69.7 mA, which is the same condition as that in Figs. 4 and 5. Figure 6(a) shows optical spectra for L=8.0 cm where the laser output is less stable, i.e., almost the local minimum of the stability curve in Fig. 4. The laser output initially stays stable for no or little optical feedback. For small external feedback, the relaxation oscillation frequency grows and the laser output power becomes unstable. In this region, we observe small relaxation oscillation frequency spectrum as a period-1 oscillation besides the main optical spectrum. Then, with the increase in external reflectivity, the external cavity mode is excited. In this quasi-periodic or weakly chaotic state, the spectrum shows an entangled state of relaxation oscillation with the external cavity mode. An example of the external cavity mode frequency is indicated by an arrow in the figure. With further increase of the external reflection, the laser output becomes chaotic which results in a completely coherence collapse state. In Fig. 6(a), the laser output becomes unstable at a rather small fraction of the external feedback. Thus, the laser output power evolves from fixed state (spectrum a) into periodic (spectra b and c), quasi-periodic (spectrum d), and, finally, weakly chaotic (spectrum e) states as seen from these spectra. The calculated frequency corresponding to the external mode from the spectrum is 1.56 GHz. As discussed in the previous work, the external cavity mode frequency is always less than the frequency calculated from the external cavity length ($c/2L$=1.87 GHz in this case). Within the range of the external reflectivity in the experiments, no completely chaotic state was observed. Figure 6(b) shows another example of optical spectra for L=10.5 cm where the stability of the laser output is much enhanced, i.e., one of the stability peaks in Fig. 4. The laser output power remains stable even for a

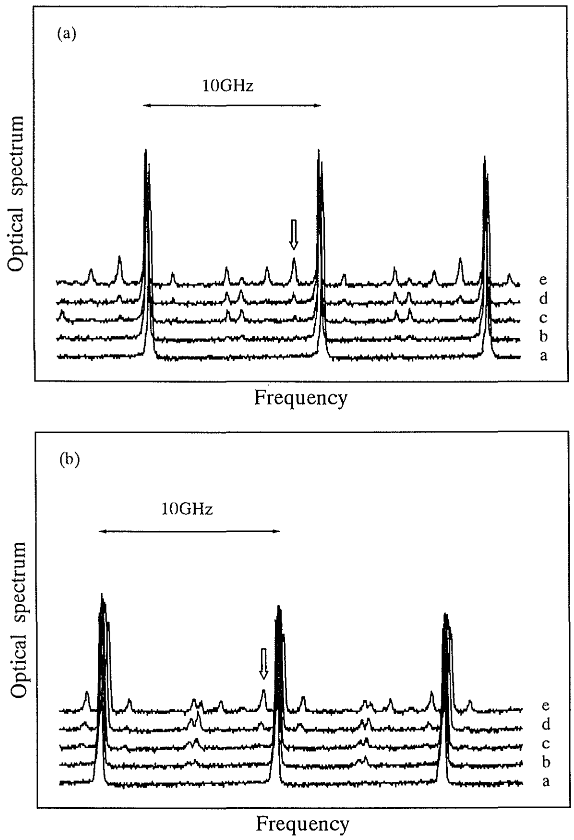

Fig. 6. Optical spectra at different external reflectivities. The injection current is also 69.7 mA. (a) L=8 cm and the reflectivities are a: 0, b: 2.6, c: 4.0, d: 4.4, and e: 7.9%. (b) L=10.5 cm and the reflectivities are a: 0, b: 7.3, c: 7.8, d: 8.5, and e: 9.4%. Arrows in the figure indicate examples of the external cavity mode frequency.

larger value of the external reflectivity (see spectrum b), but the ranges of periodic and quasi-periodic states of the laser output for the variations of the external reflectivity are small and the power soon evolves into unstable or quasi-periodic oscillations. An example of external cavity mode frequencies is indicated by an arrow. This trend is also compatible with the previous theoretical results.[12]

4. Conclusions

We investigated the periodic enhancement of the stability in semiconductor lasers with optical feedback along the external cavity position as well as the change in relaxation oscillation frequency for variations of the external cavity length. The experimentally obtained results were well coincident with the theoretical ones derived from direct numerical simulations from the rate equations and the linear stability analysis. As expected, the relaxation oscillation frequency plays an important role in the evolution of chaotic bifurcations in the nonlinear system. The period obtained by the numerical simulation and the experiments is exactly equal to the length corresponding to the relaxation oscillation frequency of the solitary laser. In the theoretical treatment, Murakami *et al.*[12] obtained the bifurcation boundaries for periodic, quasi-periodic, and chaotic states from the numerical calculation based on the rate equations. However, it is not easy to distinguish quantitatively such boundaries in the experiments. We have thus shown only the critical reflectivity at which the laser output evolves into periodic oscillation from a fixed stable state. The results obtained are very important for the practical applications of semiconductor lasers, namely, one may stabilize the laser operation by appropriately setting the system parameters even in the presence of optical feedback.

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