Vol 12 No 10, October 2003
1009-1963/2003/12(10)/1120-04

Chinese Physics

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and IOP Publishing Ltd

Low frequency fluctuation with two external cavity reflectors

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(Received 17 April 2003; revised manuscript received 23 May 2003)

The dynamics of a semiconductor laser with two optical feedbacks is studied in this paper. A new set of nonlinear rate equations that can describe external cavity semiconductor lasers with any amount of two optical feedbacks is proposed. It is found that when the laser is biased above the threshold and subjected to one feedback, the other feedback can induce low-frequency fluctuations.

Keywords: semiconductor laser, double optical feedbacks, low-frequency fluctuations
PACC: 4265, 4265T, 4230Q

1. Introduction

Semiconductor lasers have many useful properties that are desirable for applications in the field of optical communication.[1,2] Semiconductor lasers subjected to a single external feedback exhibit a rich variety of nonlinear behaviours. For instance, either weak or strong feedback can be used to realize single-mode narrow linewidth operation, while moderate feedback causes the linewidth to increase dramatically up to several tens of gigahertz. This drastic linewidth broadening is called coherence collapse.[3] At moderate feedback level, intermittent drops in light intensity, each followed by a gradual increase, have been observed near the threshold and in frequency domain, these drops manifest themselves as the low-frequency fluctuation (LFF).[4,5] The dynamics of semiconductor lasers with a single feedback have been studied extensively and the basic mechanism for LFF occurrence is well understood.[6,7]

The idea of using a second delayed optical feedback was initially proposed as a means to stabilize a chaotic laser diode pumped far above the threshold in the coherence regime. Rogister *et al*[5] investigated this scheme theoretically at a pump level near threshold, paying close attention to the steady-state solutions. In this paper, we report that the second feedback may cause LFF when the laser diode is biased above the threshold and subjected to one feedback.

2. Theory model

The single-mode semiconductor laser subjected to a weak or moderate external optical feedback is described by the Lang and Kobayashi equations. These equations were extended to describe semiconductor lasers with two optical feedbacks under the condition of weak or moderate feedbacks.[8] In this paper, we give a set of rate equations that can be used to describe semiconductor lasers with arbitrary amounts of two optical feedbacks. We assume that the two optical feedbacks return back to the laser cavity by front facet and back facet according to the model of Fig.1, where $R_{\rm ext1}$ and $R_{\rm ext2}$ are the reflection coefficients of two external cavities, R_1 and R_2 are reflection coefficients of the two laser facets. $R_{\rm eff1}$ and $R_{\rm eff2}$ are effective reflection coefficients of two facets after multiple reflections, which can be described by the well-known expression, $R_{\rm eff1}^{1/2} = R_1^{1/2} \cdot f_1$, $R_{\rm eff2}^{1/2} = R_2^{1/2} \cdot f_2$. Here f_1 and f_2 can be calculated as follows:[9]

$$\begin{aligned} f_1 =& 1 + \frac{\sqrt{R_{\rm ext1}}(1-R_1)}{\sqrt{R_1}} \times \sum_{p=1}^{\infty} \sqrt{\frac{S(t-p\tau_1)}{S(t)}} \\ & \times (-\sqrt{R_1 \times R_{\rm ext1}})^{p-1} \\ & \times \exp[-{\rm j}(\omega p\tau_1 + \phi(t) - \phi(t-p\tau_1))], \end{aligned} \tag{1}$$

$$\begin{aligned} f_2 =& 1 + \frac{\sqrt{R_{\rm ext2}}(1-R_2)}{\sqrt{R_2}} \times \sum_{p=1}^{\infty} \sqrt{\frac{S(t-p\tau_2)}{S(t)}} \\ & \times (-\sqrt{R_2 \times R_{\rm ext2}})^{p-1} \\ & \times \exp[-{\rm j}(\omega p\tau_2 + \phi(t) - \phi(t-p\tau_2))], \end{aligned} \tag{2}$$

where τ_1 and τ_2 are the round-trip times in the two external cavities respectively, ω is the frequency, $\phi(t)$ is the output phase at the laser facet, p is an integer,

which represents the pth reflection. The facet losses of the semiconductor laser are given by the effective reflectivity,

$$a_{\mathrm{e}} = \frac{v_{\mathrm{g}}}{2l} \ln\left(\frac{1}{R_1 R_2 |f_1|^2 |f_2|^2}\right), \tag{3}$$

where v_{g} is group velocity, l is length of laser cavity. From the derivative equation of electrical field,[10] the rate equations of photons (s) and phase (ϕ) are derived as

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \left(g(n,s) - \frac{1}{t_{\mathrm{p}}} + \frac{\ln|f_1|^2}{t_{\mathrm{c}}} + \frac{\ln|f_2|^2}{t_{\mathrm{c}}}\right) S + R_{\mathrm{sp}} + F_{\mathrm{S}}(t), \tag{4}$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \frac{1}{2}\beta_{\mathrm{c}}\left(g(n,s) - \frac{1}{t_{\mathrm{p}}} + \frac{\ln|f_1|^2}{t_{\mathrm{c}}} + \frac{\ln|f_2|^2}{t_{\mathrm{c}}}\right) + \frac{\arg f_1}{t_{\mathrm{c}}} + \frac{\arg f_2}{t_{\mathrm{c}}} + F_{\phi}(t), \tag{5}$$

where $|f_1|$, $|f_2|$, $\arg f_1$ and $\arg f_2$ are the complex magnitudes and phase angles of f_1 and f_2, respectively, t_{c} is the round-trip time of laser cavity, t_{p} is the photon lifetime, β_{c} is the linewidth enhancement factor, $g(n,s)$ is the gain in the laser cavity.

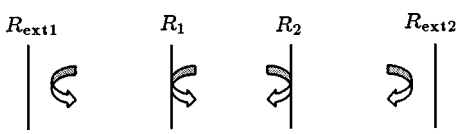


Fig.1. Model of the semiconductor laser with two feedbacks.

The rate equation for the number of carriers is unaffected by the optical feedbacks. It remains the well-known expression.[10,11]

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{I}{q} - \frac{N}{t_n} - g(n,S)S + F_N(t), \tag{6}$$

where $F_N(t)$, $F_\phi(t)$ and $F_S(t)$ are the Langevin noise sources associated with the carrier, photon, and phase respectively. I is the injection current, t_n is the carrier lifetime. Their detailed expression and calculation method can be found in the Ref.[9]. Rate Eqs.(4),–(6) account for the case of semiconductors with two external cavities. In the following research work, this set of rate equations are used as a theoretical model. The nonlinear rate Eqs.(4), (5) and (6) are solved using the sixth-order Runge–Kutta algorithm. Because we intend to investigate the deterministic dynamics of external cavity semiconductor lasers in this paper, the Langevin noise sources are omitted in the numerical simulation.

3. Simulation and result analysis

The dynamics properties of semiconductor lasers subjected to a single external feedback have been studied extensively in Refs.[5]–[7]. We present the simulation results for the single feedback laser to validate the new model.

The semiconductor lasers with an external cavity have four different operation regions as shown in Fig.2. The external-cavity laser shows different dynamic properties in different operation regions. When the external reflectivity is less than –30 dB, the laser operates stably and the linewidth is narrower than that without external feedback (region I). Region II is the chaotic region, where the coherence collapse happens. When the external reflectivity lies between –10 – –5 dB, the laser operates in region III, where the low-frequency fluctuation appears. Region IV is characterized by the stable operation at a high feedback strength. This region can be reached when the output facet of the laser is antireflection coated. The simulation results approve our new model for the external cavity laser, because it is very close to the theoretical results given in other papers.

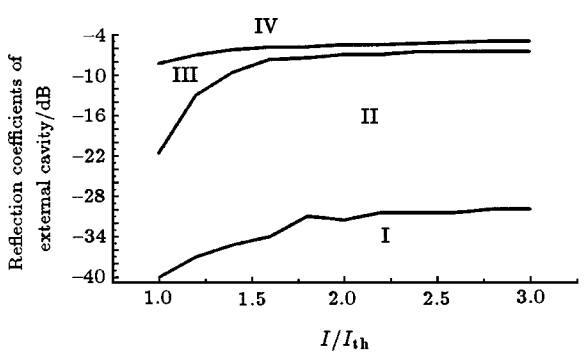


Fig.2. Operation regions of semiconductor lasers with a single feedback.

In our simulation, firstly, the rate equations are solved without the second feedback, R_{ext1} and τ_1 are set at 0.1 and 2 ns, respectively. The averaged output power is stable and the laser diode shows an external mode characteristic. As shown in Fig.3, the peaks near the inverse of external cavity round-trip time and the higher harmonics are found in the power spectrum.

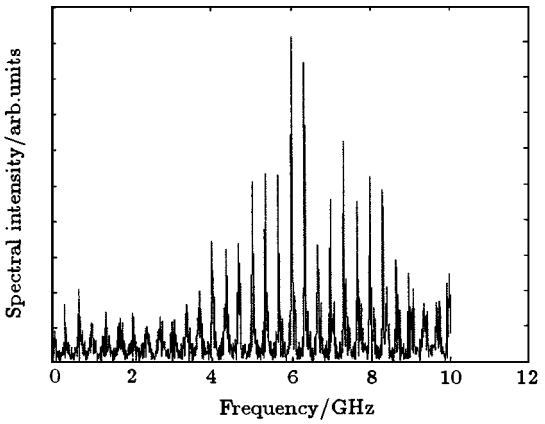


Fig.3. Power spectrum of semiconductor lasers with a single feedback.

It can be seen that the laser operates in region II in Fig.2, where the averaged output power is stable and no LFF appears. Then the second feedback is introduced in the simulation, and R_{ext2} and τ_2 are set at 0.25 and 1 ns, respectively.

It is found that the second feedback with a shorter round-trip may cause LFF. The sudden dropouts of the output power occur at aperiodic intervals, and are followed by gradual stepwise recoveries, as shown in Fig.4(a). The recovery time steps equal the round-trip time of the second feedback and the steps needed to reach the high-intensity state are about 10–20. In the LFF system with two external cavities, the averaged output power drops to the power level near the stable value without feedback, while, in the conventional LFF system, the intensity drops to the value near zero. The un-averaged time trace of the photon numbers shows erratic pulses in the process of build up after dropouts. We found the same numerical phase trajectories as those found in the LFF system near the threshold, as shown in Fig.4(b). $\Delta N = N - N_{\text{th}}$, N_{th} is the number of carriers at the threshold. According to the phase space trajectories, the intensity drop and build up process can be expressed by Sano's theory.[6] Starting from zero feedback, where only there is one stable point, the number of the fixed points increases in pairs when the feedback is increased. Of each pair, one shows instability (known as antimode) and the other does not (known as compound-cavity mode).[12] The drops are initiated by the collision between compound cavity modes and the associated antimode (crisis). After the crisis, the carrier number increases to a value near that at the threshold and the phase difference shifts to a smaller value, which is almost equivalent to the stable-state value without feedback. The intensity build up process originates from the change in the lasing mode, from the smaller phase difference modes to larger phase-difference modes.

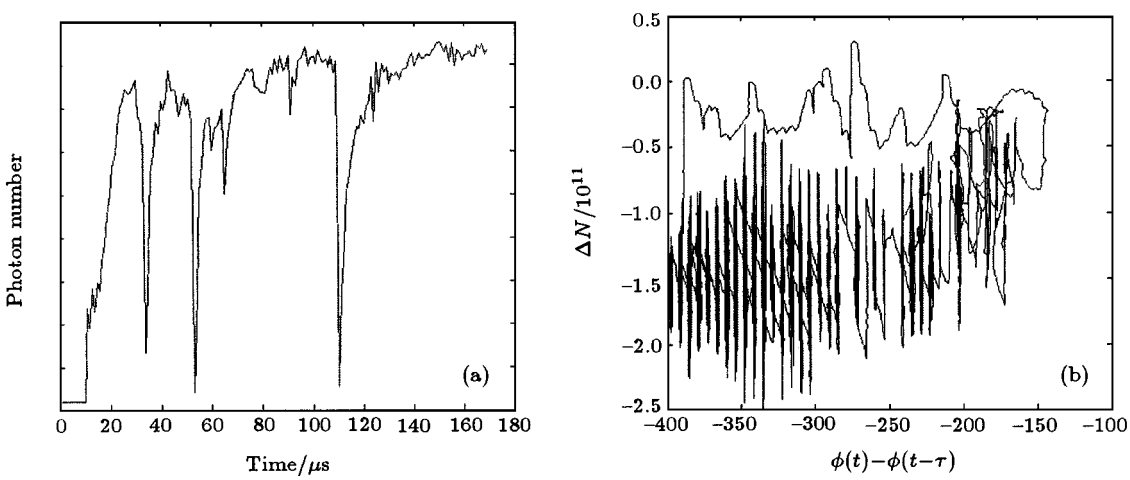


Fig.4. (a) Time trace of the number of photons. (b) Numerical phase space trajectories of the LFF system.

It is found that the time interval between two drop events depends on the feedback power of the second feedback. The dropout events become more and more infrequent when the feedback power from the second external cavity increases, as shown in Fig.5(a). When R_{ext2} increases to 0.6, the drop events disappear in the calculation duration. Here, parameters of the first reflection and round trip time of the second reflection are the same as those used in Fig.2. The dropout events are frequent when the bias current is in the range of 2–3 times of the laser solitary threshold, as shown in Fig.5(b). $< T >$ increases dramatically when

the pump current decreases to a value near the laser diode solitary threshold. The dropout events become more and more infrequent when the bias current increases to the value larger than 3 times of the laser diode solitary threshold. When the pump current increases to 3.5 times of the laser diode solitary threshold, the dropout events disappear in the calculation duration.

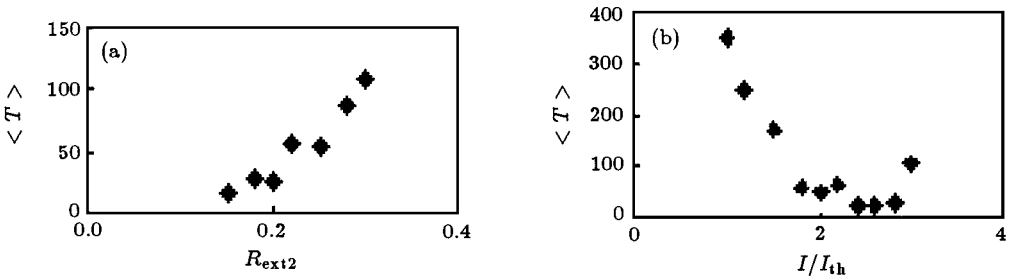


Fig.5. $< T >$ is the average of the time of dropout intervals (ms). (a) $< T >$ versus $R_{\rm ext2}$, (b) $< T >$ versus $I/I_{\rm th}$.

4. Conclusion

In conclusion, we have proposed a new set of nonlinear rate equations that can describe the external cavity laser with any amount of two optical feedbacks. We found that another feedback can induce low-frequency fluctuations when the laser is biased above the threshold and subjected to one feedback.

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