Theoretical study of laser diodes with double optical feedbacks

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A new set of nonlinear rate equations that can describe the external cavity semiconductor laser with two optical feedbacks is proposed. The dynamics of the semiconductor laser with two optical feedbacks are studied. It is found that when lasers are biased above the threshold and operate in regime V, another feedback can induce low frequency fluctuations.

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Semiconductor lasers have many useful properties that are desirable for application in the optical communication system. Semiconductor lasers with single external feedback exhibit rich variety of nonlinear behaviors. For instance, either weak or strong feedback can realize single-mode narrow-linewidth operation, while moderate feedback cause the linewidth to increase dramatically up to several tens of gigahertz. This drastic linewidth broadening is called coherence collapse[1]. At moderate feedback levels, intermittent drops in light intensity, each followed by a gradual increase, have been observed near the threshold and in frequency domain, and this drops manifest themselves as low frequency fluctuation(LFF). All these nonlinear phenomena are researched and explained[2,3] on the basis of the well-known Lang-Kobayashi equations of single feedback[3]. 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[4,5], and Rogister *et al.*[4] investigated this scheme theoretically at pump level near threshold, paying close attention to the steady state solutions. According to Sano's theory of the LFF in a single-mode semiconductor laser, the second feedback was used to suppress LFF by destroying the antimodes that are responsible for the LFF crises or by pushing them far away from the external cavity modes.

The single-mode semiconductor laser subjected to weak to moderate external optical feedback is described by the Lang and Kobayashi equations. Those equations were extended to the problem of laser with two optical feedbacks under the condition of weak to moderate feedback[5]. In this paper, we give a set of rate equations that can be used to the problem of arbitrary amounts of two optical feedbacks. We assume that two optical feedbacks return to laser cavity by front facet and back facet, respectively, according to the model of Fig. 1.

The effective reflection coefficients of two facets after multiple reflections are described by the well-known

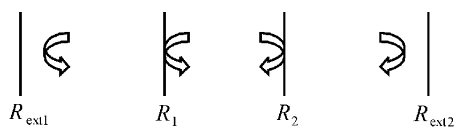

Fig. 1. Model of the lasers with two external feedbacks.

expression. $\sqrt{R_{\rm eff1}} = \sqrt{R_1} \times f_1$, $\sqrt{R_{\rm eff2}} = \sqrt{R_2} \times f_2$, f_1, f_2 can be calculated as follows[6]

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

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

where τ_1 and τ_2 are round-trip time in two external cavities, respectively. The facet losses of semiconductor lasers are given by the effective reflectivity,

$$a_m = \frac{v_g}{2l} \ln\left(\frac{1}{R_1 R_2 |f_1|^2 |f_2|^2}\right). \quad (3)$$

From the derivative equation of electrical field[7], the rate equations of photons and phase are derived

$$\frac{{\rm d}S}{{\rm d}t} = \left(\frac{g(n,s)}{1+\varepsilon S} - \frac{1}{t_p} + \frac{\ln|f_1|^2}{t_c} + \frac{\ln|f_2|^2}{t_c}\right) S + R_{sp} + F_s(t), \quad (4)$$

$$\frac{{\rm d}\phi}{{\rm d}t} = \frac{1}{2}\beta_c \left(\frac{g(n,s)}{1+\varepsilon S} - \frac{1}{t_p} + \frac{\ln|f_1|^2}{t_c} + \frac{\ln|f_2|^2}{t_c}\right) + \frac{\arg f_1}{t_c} + \frac{\arg f_2}{t_c} + F_\phi(t), \quad (5)$$

where $|f_1|, |f_2|, \arg f_1$, and $\arg f_2$ are the complex magnitude and phase angle of f_1, f_2, respectively. They can be calculated using methods that are presented in Ref. [8]. t_c is the round-trip time of laser cavity and β_c the linewidth enhancement factor. The rate equations for carriers number are not affected by the optical feedback. It remains the well-known expression[9]

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

where $F_N(t), F_\phi(t), F_S(t)$ are the Langvin noise sources associated with carrier, photon, and phase rate equation, respectively. Their detailed expression and calculation method can be found in Ref. [6]. Rate Eqs. (4),(5) and (6) account for the case of multiple reflections from two facets of laser. They can also be used for the case of multiple reflections from same facet of semiconductor laser after the expression of effective reflection coefficient are changed. If R_{ext1} or R_{ext2} equals to 0, they are same with that given by Pascal Besnard *et al.*[10] which can be used in the case of external cavity semiconductor laser with arbitrary amount of single optical feedback. In follows, this set of rate equations is used as theoretical model.

The nonlinear rate Eqs. (4), (5) and (6) are solved using sixth-order Runge-Kutta algorithm. The RF spectrum is calculated by the FFT method from the resultant time domain data. Figure 2 represent the RF spectra at various amounts of the feedback for $I_{\text{b}} = 3I_{\text{th}}$. I_{b} and I_{th} are the bias current and threshold current of the diode laser, respectively. Although RF spectra of diode laser with single strong feedback are well known, we present them here briefly in order to compare our result with double feedbacks. In the simulation, firstly, external system is subjected to single strong feedback, and the external reflectivity and the round-trip time are 0.2 and 3 ns, respectively. The RF spectrum with single strong feedback is given in Fig. 2(a). In this system, external cavity mode dominates the operation of diode lasers, the peaks are located near the inverse of round-trip time of the external cavity and it's higher harmonics. These peaks have been attributed to a beating phenomenon between external cavity modes[10].

Then the second feedback is included, the round-trip time of the second feedback is set to 10 ns and the reflectivity of external reflector is changed. When second feedback is weak (Fig. 2(b)), no obvious change take place in the RF spectrum. Only some peaks near the harmonics of 0.33 GHz decrease, but no peaks appear near 1 GHz and its harmonics, which means that second weak feedback has not important influence on the operation state. When R_{ext2} is further increased, a considerable change in the RF spectrum occurs as shown in Fig. 2(c). The peaks near 1 GHz and its harmonics appear and coexist with the peaks near 0.33 GHz harmonics. Although $C_2 \ll C_1$, the peaks near 1 GHz harmonics are stronger than those near 0.33 GHz harmonics. C_1, C_2 are the feedback parameter associated with first and second feedback, respectively, they are given by $C = \gamma\tau\sqrt{1+a^2}$[12], where γ is the feedback rate, τ is the external cavity round-trip time and a is linewidth enhancement factor. When $R_{\text{ext2}} = 0.1$, the peaks near 0.33 GHz and its harmonics are almost suppressed totally (Fig. 2(d)). In this condition, we have not found obvious change in the RF spectrum by increasing R_{ext1} in our numerical calculation, even for $R_{\text{ext1}} = 0.5 - 0.8$. According to our numerical simulation results obtained by changing the round-trip time of two external cavities, the shorter external cavity mode always dominates the operation state of the laser under the condition of two strong feedbacks.

F. Rogister *et al.* found that when the bias current is near the solitary laser threshhod, the LFF can be suppressed by another feedback which can destruct antimodes that are responsible for crisis and stabilize the laser through creation of new maximum gain modes. But in present paper, we found that second feedback may induce low frequency fluctuation when the external cavity laser is biased above threshold and operates in regime V.

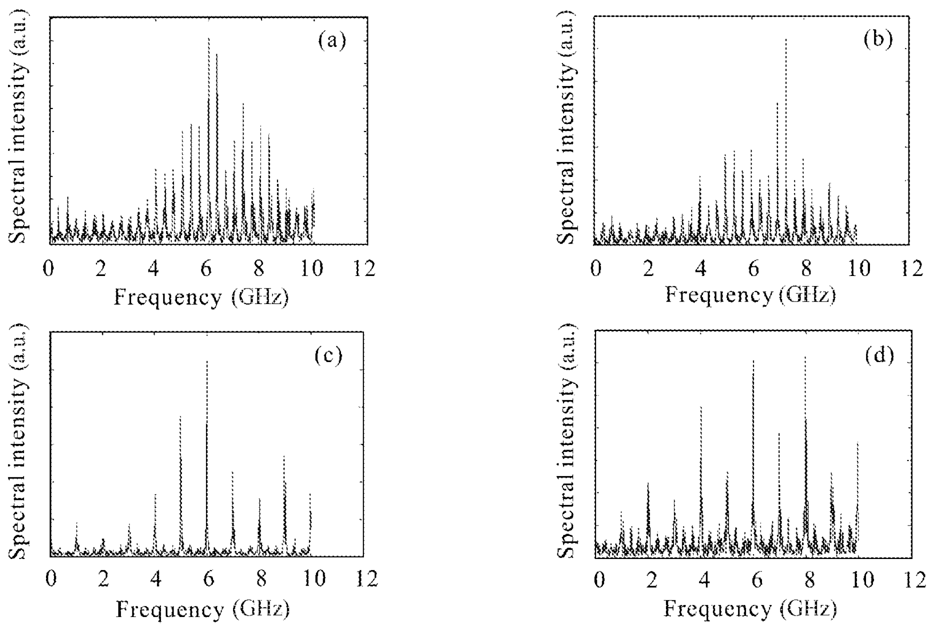

Fig. 2. Simulated RF spectra for the external cavity laser with double feedbacks. (a) $R_{\text{ext2}} = 0$, (b) $R_{\text{ext2}} = 0.001$, (c) $R_{\text{ext2}} = 0.05$, and (d) $R_{\text{ext2}} = 0.1$.

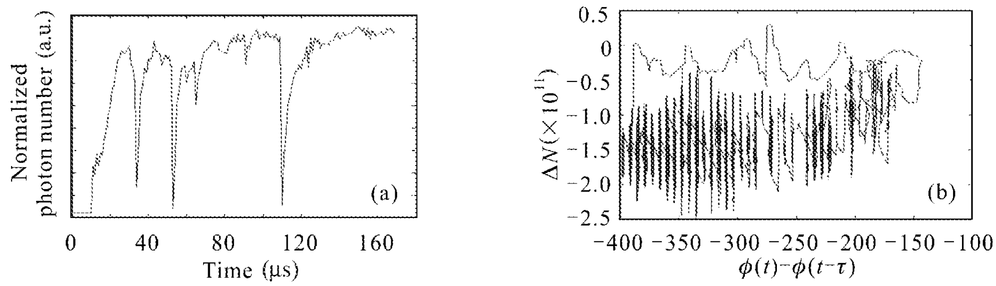

Fig. 3. (a) Time trace of photon number showing the intensity dropout characteristic for the LFF. $R_{\text{ext2}} = 0.1$, $\tau_1 = 2000$; $R_{\text{ext1}} = 0.25$, $\tau_2 = 1000$. (b) Numerical phase space trajectories of the LFF system.

The LFF under two strong feedbacks is very similar to that with single feedback. As found in the single feedback system[3,10], the sudden dropout of the output power occurs at aperiodic intervals, and followed by gradual, stepwise recoveries (in Fig. 3(a)). The recovery time step equals to the round-trip time of second feedback and the steps needed to reach the high intensity state are about $10-20$. It shows that it is the second feedback with shorter round-trip time that causes the dropouts. In the LFF system, the output power drop to the power level near the stable value without feedback, while, in the conventional LFF system, the intensity drop to the value near 0. Because the laser is biased above the threshold in the new LFF system. The unaveraged time trace of the photon numbers shows erratic pulse in the process of build up after dropout, indicatings exiting of some kind of mode locking in the build up process[13]. We found same numerical phase trajectories with that found in the LFF system near threshold (in Fig. 3(b)). In Fig. 3(b), $\Delta N = N - N_{\text{th}}$, where N_{th} is the threshold carrier number. According to the phase space trajectories, the intensity drop and build up process can be expressed by Sano's theory[2]. The drops are initiated by the collision between the quasi-attractor in one of compound cavity modes and the associated antimodes (crisis). After the crisis the carrier number increase to value near threshold 0, and the phase difference shift to 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. All these indicate that this kind of intensity drop events may have same physical cause with those take place when the laser is biased near threshold and subject to single moderate feedback.

It was found that the time interval between two drop events depends on the feedback power of the second feedback. The dropouts became more and more infrequent when the feedback power from the second external cavity increased. That is the same with the experimental result found in the conventional LFF system[14]. When R_{ext2} increased to 0.6, the drop events disappeared in the calculation time duration. This also can be explained by the potential barrier theory of the conventional LFF proposed by Henry and Kazarinov[4]. The potential carrier height grows with the feedback strength k, and for sufficiently strong feedback, system cannot cross over the potential barrier and keep stable operation. We also studied the dependence of dropout events statistics on the bias current. It was found that the dropout events are frequent when the bias current is in the range of $2-3I_{\text{th}}$. The average dropout interval time increased dramatically when the pump current decreased near to laser diode solitary threshold. The dropout events became more and more infrequent when the bias current increased to the value larger than $3I_{\text{th}}$. When the pump current increased to $3.5I_{\text{th}}$, the dropout events disappeared in the calculation time duration.

In conclusion, a new set of nonlinear rate equations that can describe the external cavity laser with any amount of two optical feedbacks is proposed in this paper. The dynamics of the semiconductor laser with two optical feedback are theoretically studied. It is found that another feedbacks can induce low frequency fluctuation when laser is biased well above the threshold and operates in regime V.

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