Low-frequency fluctuation in multimode semiconductor laser subject to optical feedback

Xu Zhang (张 旭), Huiying Ye (叶会英), and Zhaoxin Song (宋兆欣)

Information Engineering College of Zhengzhou University, Zhengzhou 450052

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Dynamics of a semiconductor laser subject to moderate optical feedback operating in the low-frequency fluctuation regime is numerically investigated. Multimode Lang-Kobayashi (LK) equations show that the low-frequency intensity dropout including the total intensity and sub-modes intensity is accompanied by sudden dropout simultaneously, which is in good agreement with experimental observation. The power fluctuation is quite annoying in practical applications, therefore it becomes important to study the mechanism of power fluctuation. It is also shown that many factors, such as spontaneous emission noise and feedback parameter, may influence power fluctuation larger than previously expected.

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Subjected to external, delayed, and optical feedback, laser diodes present a large variety of different dynamical behavior. One of the most attractive phenomena found in semiconductor lasers with optical feedback is the recurrent appearance of sudden drops in the light intensity emitted by the laser under constant or modulated current driving[1]. Such dropout occurs under the condition that the injection current is close to the laser threshold with moderate feedback level. Then after dropout event the average laser intensity gradually recovers, only to drop out again after some unfixed time.

Numerical work in which the single-mode Lang-Kobayashi (LK) equations[2] was analyzed has explained the nature of the low-frequency fluctuation (LFF) as chaotic recurrence with a drift among the chaotic ruins of the destabilized external cavity modes[3]. The dropout event is initiated when the trajectory on its drift towards the maximum gain mode collides with a nearby saddle and reaches the state of zero intensity following its unstable manifold. Subsequently, the laser returns slowly to full power following a trajectory that meanders through the chaotic ruins of the destabilized external cavity modes[4].

The physical mechanism of the power dropout in the LFF regime is still to be debated. Many works have used the well-known LK equations to simulate this phenomenon. The single mode of the laser is often assumed, neglecting the multimode effect and spontaneous emission noise[5]. In this paper we demonstrate the LFF of multimode laser with spontaneous emission noise in order to obtain the output that resembles experimental observations.

Our experiments aim to provide a detailed characterization of the intensity output of the semiconductor laser with optical feedback. The experimental setup is schematically shown in Fig. 1. It consists of multimode semiconductor laser (HL 7851) with the threshold current of 90 mA. The temperature is controlled at (25 ± 0.1) °C, and the frequency of the signal generator is set to 73 Hz and its peak-to-peak value is 736 mV. A speaker is placed 60 cm away from the lens which is coated with a reflecting film. In order to get the feedback light, a delay time of 4 ns is introduced. The attenuator is mainly used to get the stable output of the laser intensity.

The combination of emitted and reflected light is received by a photodetector. By analyzing the spectrum of the mixed light, we get the intensity output of multimode laser shown on the digital oscilloscope, meanwhile we record the optical spectrum of the laser by optical spectrum analyzer. It demonstrates that the modes close to the maximum wavelength exhibit sudden dropout in power and the sub-modes intensity undergo a dropout simultaneously with the dominant mode. It also notes that the sub-modes intensities do not occur, or are barely visible. The simulation results shown later confirm the correctness of our experimentation. In our experiment, the amplitude of the self-mixing signal is obtained, and its output power can be calculated. Figure 2

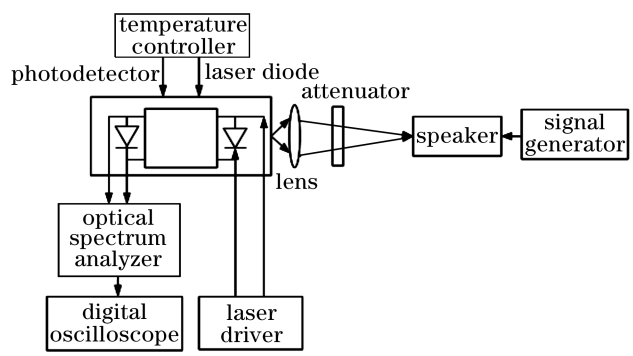

Fig. 1. Schematic of the experimental setup.

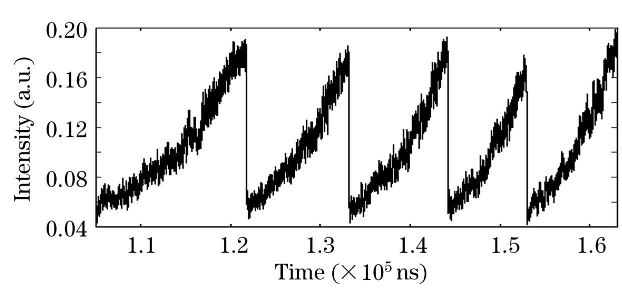

Fig. 2. Experimental LFF phenomenon.

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depicts the experimental time series of LFF.

The model used to describe the multi-mode case of a semiconductor laser with an external cavity is a generalization of the single-mode LK equations for the complex electric field $E(t)$ and the carrier population $N(t)$. Suppose that there are M solitary modes, $n = 1, 2, \cdots, M_0, \cdots, M$, where the index M_0 corresponds to the central mode.

These equations can be described as[6]

$$\frac{\mathrm{d}E_n}{\mathrm{d}t} = \frac{1}{2}(1 + j\alpha)(G_n(N) - \gamma_n)E_n + \eta_n E_n(t - \tau)\exp(j\omega_n\tau) + F_n(t), \quad (1)$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{I}{q} - \frac{N}{\tau_\mathrm{e}} - \sum_{n=1}^{M} G_n(N)\left|E_j\right|^2, \quad (2)$$

where the non-linear gain $G_n(N)$ for the nth mode is expressed as

$$G_n(N) = g_0(N - N_0)[1 - (m - m_\mathrm{c})^2(\frac{\Delta\omega_\mathrm{L}}{\Delta\omega_\mathrm{g}})^2], \quad (3)$$

where α is the linewidth enhancement factor[7], γ_n is the mode-dependent cavity loss, η_n is the feedback rate for the nth mode after one round-trip, E_n is the complex amplitude of the nth mode oscillating at the frequency ω_n, $\tau = 2L_\mathrm{ext}/c$ is the external cavity round-trip time, I is the pump current, q is the magnitude of the electron charge, τ_e is the carrier lifetime, g_0 is the differential gain, N_0 is the number of carriers at transparency, m_c is the longitudinal mode number at the gain peak, $\Delta\omega_\mathrm{L}$ and $\Delta\omega_\mathrm{g}$ are the longitudinal mode spacing and the gain width of the laser material respectively. $F_n(t)$ accounts for the spontaneous emission noise, it obeys Gaussian statistics[8]

$$\langle F_n(t)\rangle = 0 \text{ and } \langle F_n(t)F_m^*(t')\rangle = R_\mathrm{sp}\delta_{mn}\delta(t - t'), \quad (4)$$

where δ_{mn} is the Kronecker's symbol and R_sp is the spontaneous emission rate. The angular frequency on the mth mode can be described as $\omega_m = \omega_\mathrm{c} + (n - M_0)\Delta\omega$, where $\Delta\omega = 2\pi\Delta v$ is the mode spacing and ω_c is the angular frequency of the central mode. Stochastic fluctuations arising from spontaneous emission noise are neglected. In our calculation, five active optical modes are taken into consideration. The parabolic gain profile is centered on the third longitudinal mode.

Next we will present the results obtained by integrating the rate equations (1) and (2) numerically using a fourth-order Runge-Kutta algorithm[9]. The parameter values corresponding to a typical index-guide GaAlAs semiconductor laser are likely used in optical system. These values are $\alpha = 4$, $\gamma_m = 5 \times 10^{11}$ s^{-1}, $\tau_\mathrm{s} = 2$ ns, $g_0 = 1 \times 10^4$ s^{-1}, $m_\mathrm{c} = 2$, $N_0 = 1.1 \times 10^8$, $R_\mathrm{sp} = 1.1 \times 10^{12}$ s^{-1}, $\Delta\omega_\mathrm{g} = 2\pi \times 4.7$ THz and $\Delta\omega_\mathrm{L} = 2\pi/\tau_{\mathrm{L}m}$ with $\tau_{\mathrm{L}m} = 8$ ps, $\eta_n = 0.08$.

The rate equations (1) and (2) can be used to obtain the relative intensity noise (RIN) of the laser in the presence of optical feedback by calculating the spectrum of intensity fluctuations. Assuming that $P_m(t)$ is the mth mode photon number, and $\bar{P}_m$ is the average value, the RIN spectrum is defined as the Fourier transform of the autocorrelation function according to the relation[10]

$$S_m(\omega) = \frac{1}{\overline{P_m^2}}\int_{-\infty}^{\infty}\langle\delta P_m(t)\delta P_m(t + t')\rangle\exp(-j\omega t')\mathrm{d}t', \quad (5)$$

where $\delta P_m(t) = P_m(t) - \bar{P}_m$ is the function at time t, the photon number can be converted to the optical power by using the well-know relation given above.

Figure 3 shows the relaxation oscillations of a solitary laser subject to weak optical feedback. Figure 4 shows the RIN spectra for external cavity laser at the condition of $I = 2I_\mathrm{th}$, where I_th is the threshold current. The feedback rates η_n are 0.0001 and 0.6 respectively.

Low frequency fluctuations occur when the laser diode is subject to moderate optical feedback. These fluctuations consist of large drops in its output, and then increase step by step in a series of power output. In literatures about the deterministic origin of LFF, it has been shown that in LFF the sudden power dropouts are caused by a merging of an attractor ruin of an external cavity mode and a saddle point[11]. The steps have duration of external cavity round-trip time and there are a random number of steps in each period. Since each mode has a different gain, this gives rise to the stepwise increase[12]. Figure 5 shows the simulation result of LFF,

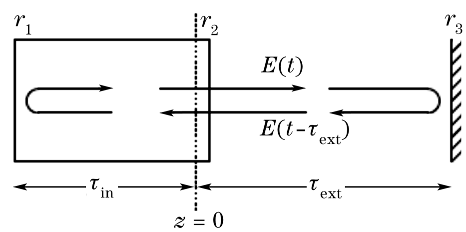

Fig. 3. Schematic diagram of a laser subject to optical feedback.

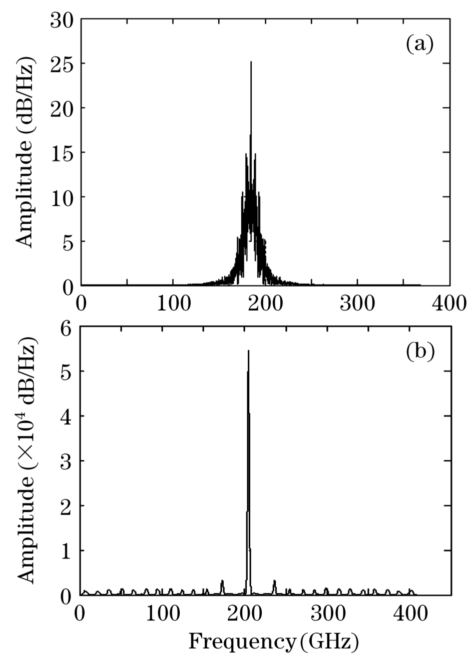

Fig. 4. RIN spectra for (a) $\eta_n = 0.0001$ and (b) $\eta_n = 0.6$.

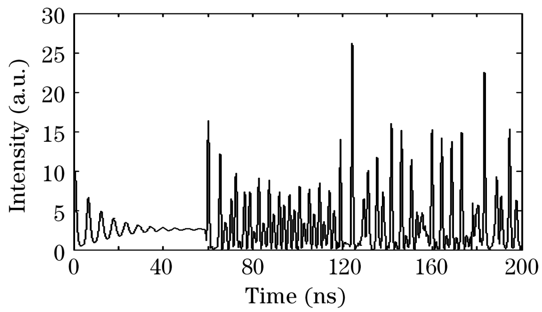

Fig. 5. Numerical simulation of LFF phenomenon.

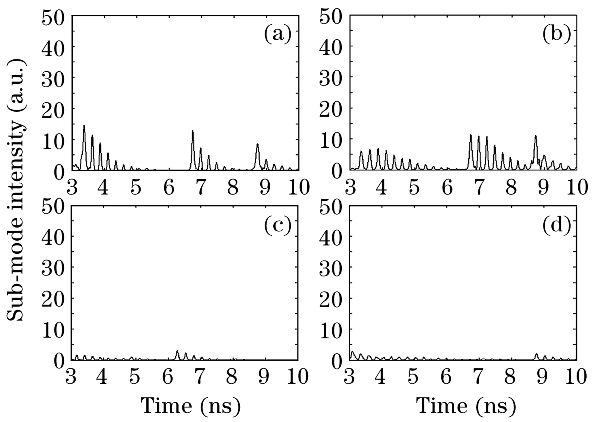

Fig. 6. Average intensities of sub-modes (a) 2, (b) 4, (c) 1, and (d) 5.

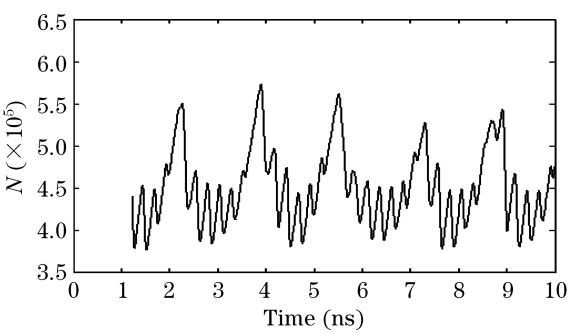

Fig. 7. Time trace of the carrier number.

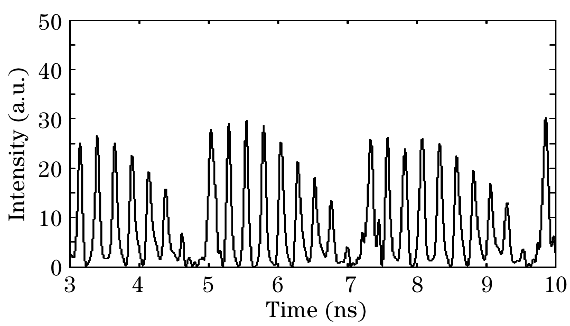

Fig. 8. Total intensity output.

the laser was biased at $I = 1.02I_{\rm th}$.

After the dropout, the intensity gradually recovers until it drops again. Between the two consecutive pulses, the laser intensity is nearly zero. Figures 6, 7 and 8 present the evolution of the modal intensity, the carrier number[13] and the total intensity output. Figure 6 shows the average intensity of sub-modes 1, 2, 4, 5 respectively. It shows that the LFF occurs in all individual modes and also in total output, and the dropout takes place almost simultaneously among all the modes, as a result, all individual modes exhibit high intensity fluctuations. This phenomenon originates from energy competition due to the different gain or loss among the longitudinal modes.

In good agreement with experiments, the sub-modes intensity outputs depress simultaneously with the dropout in the total intensity. The brusque increase of the population inversion associated with the intensity dropouts in the total intensity and triggered by the spontaneous emission noise, lasts only for a short time[14]. The average time between LFF dropout events for the multimode operation is found to be apparently shorter than that of single-mode operation.

It is important to notice that spontaneous emission noise is essential to the shape of the intensity. If we set the parameter of spontaneous emission rate as zero, that is $R_{\rm sp} = 0$, the rate of intensity dropout will be even faster. Figures 9 and 10 show the output intensity without and with spontaneous emission noise at the feedback level of 0.01 and 0.06 respectively. When the value of feedback parameter is larger, the pulse of intensity output will be sharper. It indicates that the spontaneous emission noise plays an important role in the shaping of intensity output.

A laser system with optical feedback is an infinite dimensional phase space, and therefore it is expected to show complicated dynamic behavior. It is not surprising that the LFF phenomenon in semiconductor laser is difficult to analyze. The equations have been solved numerically and the output powers versus the time for several amounts of optical feedback are obtained. The data are further processed in order to get the RIN spectrum and the value can be calculated from the frequency

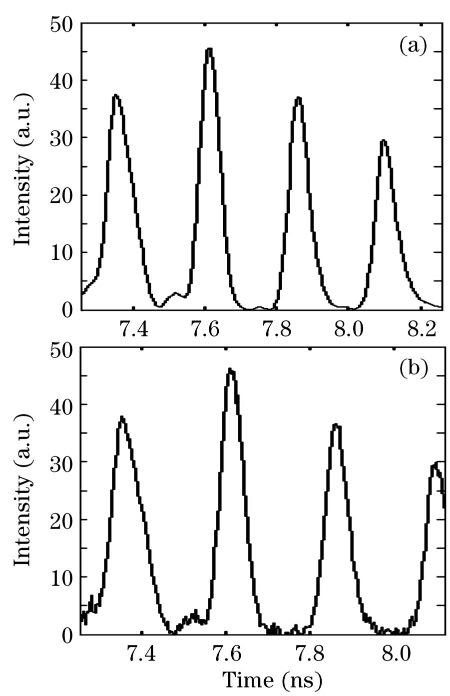

Fig. 9. Total output intensity at feedback $\eta_n = 0.01$ (a) without and (b) with spontaneous emission noise respectively.

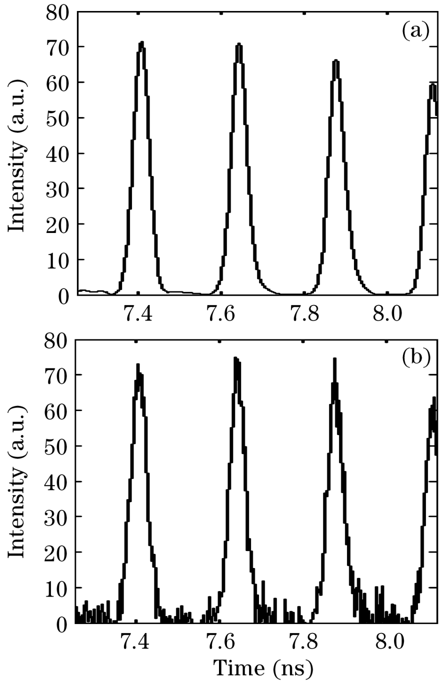

Fig. 10. Total output intensity at feedback $\eta_n = 0.06$ (a) without and (b) with spontaneous emission noise respectively.

domain. The LFF phenomenon of multimode semiconductor laser in an external cavity when the laser operates around the solitary threshold is theoretically investigated. The sub-modes intensity output of the multimode laser, the carrier number and the total output intensity with and without spontaneous emission noise are studied systematically. The main conclusions have been drawn that many factors such as feedback parameter, the modulated current, the spontaneous emission noise etc. have tremendous influence on LFF which are not attached importance to them formerly.

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