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New nonlinear dynamics in a semiconductor laser with optical self-feedback

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We demonstrate a new kind of instability of the external cavity semiconductor laser. In some parameter regimes, the external cavity system will produce short and strong optical pulses in aperiodic intervals. This instability also shows low-frequency characteristics.

Keywords: external cavity semiconductor laser, chaos
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The chaotic phenomenon in many kinds of nonlinear systems attracts extensive research.[1,2] The chaotic behaviour of semiconductor laser systems has been viewed as something amazing from a fundamental point of view but also as a nuisance to be engineered away in applications. However, since semiconductor lasers have been proposed for chaotic communication schemes, their chaotic properties have turned out to be potentially useful and now demand more attention.[3] When they are subjected to external optical feedback, the semiconductor lasers exhibit a large variety of dynamic instabilities including coherence collapse and low-frequency fluctuation (LFF), which lead to severe degradation of their temporal characteristics and increase their typical optical linewidth from 100MHz to several tens of gigahertz.[4] The LFF regime can be observed when the laser is biased near to the solitary threshold and subject to moderate optical re-injection from an assistant reflector. Recently, it has been shown that LFF takes place in a wide bias range from the solitary threshold up to as much as three times the threshold.[5] The dominant features of this kind of instability are sudden drop-outs of the optical power followed by gradual, stepwise recovery that occurs at aperiodic intervals, leading to a dramatic increase in the low-frequency noise in the radio-frequency (rf) spectrum. These drops cause kinks in the power current characteristics.[5] In this paper we report on another kind of low-frequency instability of external cavity semiconductor lasers. The external cavity system will produce strong and short optical pulses at aperiodic intervals.

The nonlinear dynamics of external cavity diode lasers have been studied by many authors[6,7] on the basis of the well-known Lang–Kobayashi[8] equations of single feedback. However, the Lang–Kobayashi equations take into account only a single feedback term, thus their validity is limited to weak to moderate feedback situations. In this paper, the effect of multi-reflection on the nonlinear dynamics of the external cavity semiconductor lasers is considered. So the improved rate equations including multi-reflection were used[9]

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

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

where t_c is the round-trip time of the laser cavity and β_c is the linewidth enhancement factor. $|f|$ and f are the complex magnitude and phase angle of the effective reflection coefficient, respectively. The expression of the effective reflection coefficient has been given by many authors.[10,11] In our calculation, we use the approximate calculation method

$$|f|^2 = \frac{1 + 2\sqrt{R}\sqrt{s(t-\tau)/s(t)}\cos(\omega\tau + \phi(t-\tau) + \phi(t)) + \dfrac{f_\mathrm{ext}}{R}\dfrac{s(t-\tau)}{s(t)}}{1 + 2\sqrt{Rf_\mathrm{ext}}\sqrt{s(t-\tau)/s(t)}\cos(\omega\tau + \phi(t) - \phi(t-\tau)) + Rf_\mathrm{ext}s(s-\tau)/s(t)},$$

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$$\arg\ f = \arctan\left\{\frac{\sqrt{f_{\rm ext}}(\sqrt{R}-1/\sqrt{R})\sqrt{s(t-\tau)/s(t)}\sin(\omega\tau+\phi(t-\tau)-\phi(t))}{1+\sqrt{f_{\rm ext}}(\sqrt{R}+1/\sqrt{R})\cos(\omega\tau+\phi(t-\tau)-\phi(t))+f_{\rm ext}\dfrac{s(t-\tau)}{s(t)}}\right\},$$

where τ is the round-trip time of the external cavity, and $f_{\rm ext}$ and R are the power reflection coefficient of the diode facet and the external cavity reflector, respectively. The rate equation for the carrier number is unaffected by the optical feedback. It remains the well-known expression[12]

$$\frac{{\rm d}N}{{\rm d}t} = \frac{I}{q} - \frac{N}{t_n} - g(n,S)S + F_{\rm n}(t), \qquad (3)$$

where $F_{\rm n}(t)$, $F_\phi(t)$ and $F_{\rm s}(t)$ are the Langevin noise sources associated with the carrier, photon and phase rate equations, respectively. Detailed expressions and calculation methods for these can be found in Ref.[12]. In this study, the Langevin noise is omitted, because the deterministic dynamics of the diode laser has been considered. The rate equations (1), (2) and (3) were solved by the sixth-order Runge–Kutta algorithm. The parameters used were set to typical values: $\beta_{\rm c}$=5, R=0.32, differential gain $2.5\times10^{-16}{\rm cm}^2$, mode confinement factor 0.3, transparent carrier density $1\times10^{18}{\rm cm}^{-3}$ and $R_{\rm sp}=1\times10^{12}{\rm s}^{-1}$.

The LFF was found to take place in the region between the regimes IV and V according to the definition in Ref.[13], which was initiated by the collision between the compound cavity mode and associated phase space trajectory that was created by the saddle-node bifurcation. The carrier number dN increases directly to threshold value, and then the phase shifts to a smaller value. The build-up process is due to the change of the lasing mode, driven by oscillation, from smaller phase-difference modes to larger phase-difference modes.[7] In this paper we show another kind of nonlinear dynamic phenomenon that has been omitted in previous research.

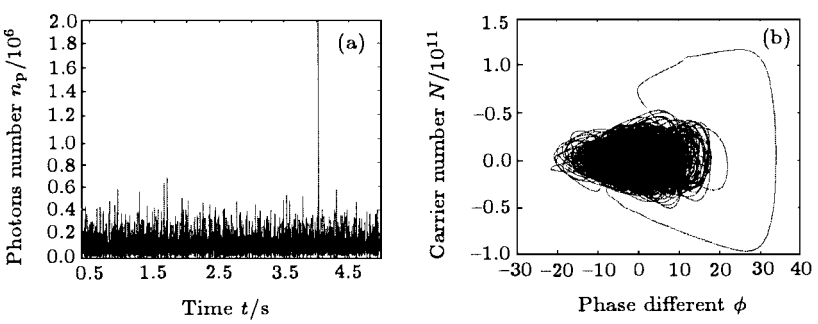


Fig.1. (a) Time evolution of the photon number $n_{\rm p}$, and (b) phase space trajectory: I=1.6Ith; Rext=0.0006 (Ith represents the solitary threshold current).

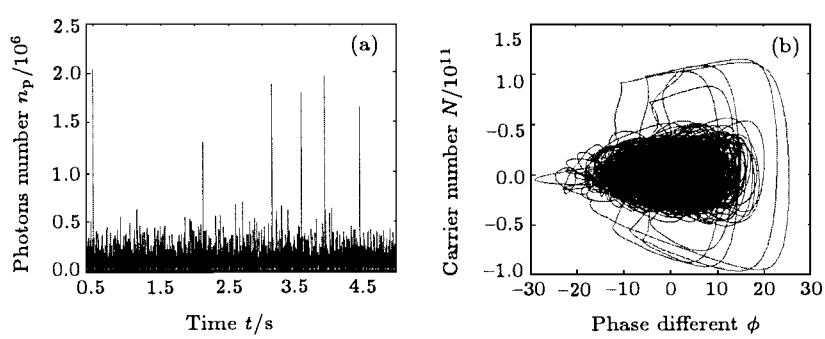


Fig.2. (a) Time evolution of the photon number and (b) phase space trajectory: I=1.6Ith; Rext=0.0008.

When the system is in the chaotic region, the system randomly produces strong optical pulses at aperiodic intervals, as shown in Figs.1(a) and 2(a). Like the LFF, these short and aperiodic strong pulses also show low-frequency characteristics and the average time interval between two strong pulses decreases with the increase of the feedback strength. The averaged full width of this kind of strong pulse is about 30–40ps. We have not found an obvious relationship between the pulse width and the feedback strength.

This chaotic process begins with the rapid increase of the carrier number and the phase difference shifts to a smaller value, where it remains almost constant. But the carrier number decreases rapidly, and then the carrier increases quickly and the system switches to the new mode, as shown in Figs.1(b) and 2(b). This starts from the upper half of the chaotic attractor and ends at the lower half of the chaotic attractor (Figs.1 and 2). It can be explained that the system spends most time on the chaotic attractor and visits the antimode randomly. When the system reaches the antimode, the small deviation of the trajectory from the fixed point grows exponentially.[7] So, like the LFF, this chaotic process may also be initiated by a collision between the phase space trajectory and antimodes. To explain from the physical mechanism, this strong pulse shows that some kind of mode lock process takes place. The modes are the destabilized external cavity modes produced by the external reflections. It can be proven from the phase space trajectory that when the strong pulse occurs, the phase difference almost remains constant. The strong power pulse has also been predicted to exist in the LFF system.[14]

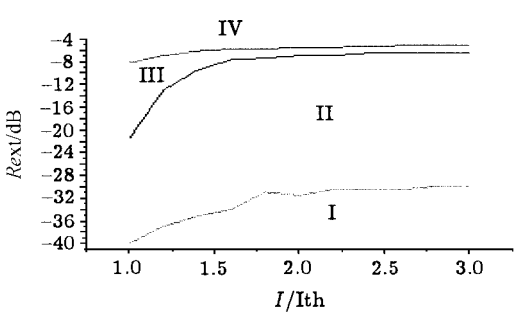


Fig.3. Calculated region for the chaotic power pulsation.

The aperiodic strong pulses occur in a wide bias current range from near solitary threshold to as much as three times the threshold current. The regions of the aperiodic strong pulses are shown in the Fig.3. Region IV is the fifth regime according to the definition in Ref.[13], which was characterized by stable operation at high feedback strength. This region can be reached when the output facet of the laser is anti-reflection coated. Region III is the LFF region calculated from the theoretical model that has already been shown and experimentally proved.[5] Region II is the region where this aperiodic strong pulse was observed. According to our calculation, region II is included in the coherence collapse regime. So this aperiodic strong optical pulse is an important characteristic of coherence collapse. There is a feedback strength threshold for the aperiodic strong pulse in the coherence collapse regime. When the feedback strength is lower than the threshold, the output power shows erratic pulsing and no strong pulse appears. When the feedback strength is larger than the threshold, the strong pulse becomes more and more frequent with the increase of the feedback, until the feedback strength reaches an upper-limit value. At that point, the low-frequency fluctuation appears. The low-frequency fluctuation can be observed by averaging the output power within the microsecond time range, while the pulse width of the aperiodic strong pulse is only in the picosecond range and cannot be observed by common detectors. With the increase of the feedback strength, the narrow linewidth, single mode stable operation, mode hop, quasi-periodic torus and chaotic attractors appear in region I. The aperiodic strong pulses take place in a wider range of feedback strength than the LFF, which shows that the random aperiodic strong pulse is a more common chaotic phenomenon in the external cavity systems.

In summary, we have shown numerically a new kind of low-frequency instability of external cavity semiconductor lasers. The randomly occurring strong pulses may be caused by some kind of mode-locked process. This chaotic phenomenon occurs in a considerably wide range of feedback and injection current.

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