Instabilities in a grating feedback external cavity semiconductor laser

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Abstract: Output power fluctuations in a grating external cavity diode laser with Littman configuration are described, showing peculiar chaotic behaviors of self-pulsation at the L-I curve kink points. Different spectral characteristics with multiple peaks are observed at upper and lower state of the self-pulsation. It is found also that P-N junction voltage jumps in a same pace with the pulsation. The observed phenomena reflect competition between different longitudinal modes, and transient variation of transverse modes in addition. These experimental results may contain information about the mechanisms of the chaotic instability in strong filtered feedback semiconductor lasers.

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References and links
1. Introduction

Lasers with a single optical frequency and narrow line-width are used and to be used widely in various important applications such as high precision measurement, laser cooling, and atomic physics researches. For this purpose a lot of efforts have been spent on researches of external cavity semiconductor lasers. The stability of such single frequency laser is of particular importance in order to meet application requirements. Instabilities of semiconductor lasers have long been one of the interesting research topics, especially for the lasers with external feedback. R.Lang and K.Kobayashi[1] presented a systematic study on the effects of external optical feedback; since then much work[2-4] were published on theoretical and experimental studies of laser diodes with various feedback levels. The laser with external feedback is also considered as a typical example of optical chaos, and has attracted many researchers. J. Mørk et al.[5] summarized researches on chaos of semiconductor laser with optical feedback. A.Hohl et al.[6,7] described power-dropout phenomena and bifurcation cascade in semiconductor lasers. E. Detoma et al. [8] presented studies on laser diode with strong filtered optical feedback.

In this letter we present experimental studies on instability and chaotic phenomena of an external cavity semiconductor laser with a Littman configuration. We observed that there are several dips in the L-I curve, and the output power at the dips jumped between three levels, resulting in self-pulsation with periods changing between millisecond and microsecond. By using a scanning Fabry-Perot etalon, we observed multi-peaks at the kinks, the numbers and intervals of the peaks were different between upper level and lower level of the self-pulsation, while a good single mode was always measured outside the kinks. A CCD camera was used to record the far field patterns. It is shown that the transverse distribution of the laser beam intensity changed at the kinks. We also measured jumps of the P-N junction voltage under a well stabilized current on the laser diode. A qualitative explanation and discussion on these phenomena will be given in the letter. We believe that these observations will be helpful not only in improving the device performances, but also for understanding optical chaos in the laser.

2. Experimental setup and results

The semiconductor laser being investigated in this work is a grating feedback external cavity laser with a typical Littman configuration, working at wavelength of 780nm, as shown in Fig. 1 schematically. The laser (Toptica LD-0780-0100-AR-1) is AR-coated with facet reflectivity down to $10^{-4}$; the grating with line constant of 1800mm$^{-1}$ (Newport 05HG1800-500-1) is placed and fixed at an incident angle of 70° to the laser beam, which was collimated by a lens (Thorlabs C230TM-B, f=4.51mm, NA=0.55) with output beam width of about 3mm. The total cavity length is about 40mm, which sets the longitudinal mode spacing to be around 3.75 GHz; a piezo transducer-driven high reflectivity mirror is used to tune the cavity length.

![Fig. 1. A schematic diagram of the external cavity laser with Littman configuration.](image1)

![Fig. 2. A typical L-I curve of the ECDL with three dips.](image2)
The laser is packaged in a copper block, and cooled and stabilized by a TE cooler at 22°C with stability of 1mK. The injection DC current can be well-stabilized with stability of better than 1μA/hour. Fig. 2 shows a typical L-I curve of the ECDL, showing that its threshold is about 35mA and the output power is around 55mW at 180mA. The laser works in a single longitudinal mode for most range of the pumping current, and can be tuned over 20GHz without mode-hopping, which is limited by the piezo driving voltage. The optical frequency can be stabilized by using a rubidium cell and feedback circuits, resulting in a stability of below 1MHz.

The L-I curve in Fig. 2 shows a wavelike feature, which is typical for an external cavity laser just as described in Ref. 1. It is noticed, however, that there are sharp dips near I=130, 145 and 180mA; and the laser shows abnormal behaviors at these dips.

Firstly the output power fluctuates periodically as shown in Fig. 3 at I ~130mA. Among them Fig. 3(b, c, d, e, f) are from the same oscillographic waveform of Fig. 3(a), but with time scales successively reduced as (a) 100ms/div, (b) 20ms/div, (c) 2ms/div, (d) 500μs/div, (e) 50μs/div, and (f) 10ms/div, among which (f) is the enlarged waveform at the falling edge of the pulse. The power fluctuation shows self-pulsation behaviors with some obvious features. (1) The output power fluctuates in stepwise with rather sharp and clear edges. (2) The power fluctuation appears with different temporal features. The lowest is in tens-millisecond range, and with basically equal period, while the highest is in several-microsecond range. (3) The power jumps between three discrete levels in a range of between ~35 and ~40mW, showing a feature of bifurcation. (4) In the middle level, the power fluctuates with basically equal amplitude and varied period, which decreases monotonically and then increases inversely, and repeat a few times, i.e. 6 times in Fig. 3(b).

![Fig. 3. Self-pulsation waveforms with different time scales: (a) 100ms/div, (b) 20ms/div, (c) 2ms/div, (d) 500μs/div, (e) 50μs/div, (f) 10ms/div.](image)

The output fluctuation at L-I dips of I ~145 and 180mA show a little bit different behaviors as shown in Fig. 4, where the output jumps periodically, and basically between two levels, whereas rarely to the third level. The ratio of durations at upper level and lower level...
varies with the injection current as shown in Fig. 4(a) and (b) for two typical examples. These behaviors show typical chaos characteristics, but with different feature from that reported in previous Ref.s.

![Fig. 4. Self-pulsation waveforms at the second kink: (a) and (b) for two injection currents with difference around 1mA. Time scale: 100ms/div.](image)

To understand the mechanism in detail, we measured the spectrum at the self-pulsations by using a scanning Fabry-Perot etalon (Toptica FPI-100, FSR=1GHz, F>300). Fig. 5(a) shows the spectra together with the power level; Fig. 5(b) is another spectrum together with the voltage on the PZT. It is noticed that there are fewer peaks with higher amplitude at upper output level than at lower level, and the intervals between the peaks are measured to be around 170MHz for upper output level and ~40MHz for lower level. In addition, the peaks in spectrum for lower level appear in groups, and the interval between groups is near the interval for upper level. As a comparison, Fig. 5(c) shows a single mode spectrum in stabilized output case. Taking different orders of scanning Fabry-Perot etalon into account, the peaks for the upper level could be attributed to different longitudinal modes; while the minor peaks in groups for lower level might be attributed to transverse modes.

![Fig. 5.(a), (b) Spectrum at upper and lower output levels measured by a scanning Fabry-Perot etalon (c) Spectrum at injection current region out-of the kinks, with an inclined line of scanning voltage.](image)
To make sure if there is any change of the transverse mode at kinks, a CCD camera was used to record far field patterns. Figure 6(a) and (b) are the patterns for upper and lower power levels respectively. Figure 6(c) gives their difference which is simply calculated by a Matlab program, where red and blue regions stand for positive and negative values, and yellow for near zero values. In comparison, the far-field patterns outside the kink were also measured. Figure 6(d) is the difference between patterns for two different current outside the kinks, where blue stands for near zero value, indicating that the patterns have different amplitudes but same distribution. It is shown that the transverse distribution of the laser beam intensity changes at the kinks indeed.

![Fig. 6. Far-field patterns for upper(a) and lower(b) output level at kinks. (c) Difference between patterns (a) and (b). (d) Difference between far-field patterns outside the kinks.](image)

Furthermore we measured the P-N junction voltage of the LD chip during the fluctuation, as shown in Fig. 7, where the output power curve was recorded simultaneously. It is shown that the voltage jumps in the same pace with the output power, that is, the voltage jumps to a higher level when the output jumps upper, and with an almost same speed. The voltage step was measured to be ~2mV, where the amplification of electronic circuit had been calibrated. Fig. 8 gives magnified curves of the output and junction voltage variation with the injection current near one of the kinks at ~180mA. It is shown that output and voltage jump simultaneously at the kink. Normally the voltage goes up with the current, whereas jumps down at the kink; meanwhile, the output power goes down slowly with the current near the kink, but goes down much faster at the kink.

### 3. Discussions

The above measured and observed results indicate that the grating feedback external cavity laser operates in chaotic instability at the injection current of kinks. It is necessary to point out that the kink positions may move around and the chaotic behaviors may change a lot, when the temperature of ECDL module is changed. It is widely recognized that there are five
states for semiconductor lasers with external feedback, corresponding to five regions in space of feedback level vs. injection current[3,5]. Our external cavity semiconductor laser is believed to work in the fifth state with strong feedback and large injection current, which should be a well stabilized single mode state; but may fall in chaos at the border with the fourth region. The theory presented by R. Lang[1] has been widely referred for cases of weak feedback; but it has to be revised for strong feedback case.

Many Ref.s on diode lasers with external feedback have studied chaotic instabilities for weak feedback and low injection current[1,2,5], that may be of practical importance in applications such as optical communications. In our external cavity laser the reflectivity of the AR-coated LD chip facet, $R_2 = r_2^2$, is in the order of $10^{-4}$, while the reflectivity of the grating for the first order diffraction is measured to be $R_g = 40\%$; thus the condition $(1 - R_2)\sqrt{R_{ext}/R_2} << 1$ for Lang’s formulas is not valid. Ref. 8 analyzed chaos in external cavity lasers with strong filtered optical feedback. The external feedback grating and the AR-coated facet are now composed to be a complex mirror with an effective reflectivity as[8]:

$$r_g(\omega) = (r_2 + r_g(\omega)e^{-i\omega\tau})/(1 + r_2 r_g(\omega)e^{-i\omega\tau}),$$

where the reflectivity of the grating has a Lorentzian form of $r_g(\omega) = r_{g0}(1 + i(\omega - \omega_g))/\Delta \omega^{-1}$; $\omega_g$ is the peak feedback frequency of the grating; the band width $\Delta \omega$ is inversely proportional to the beam width at the grating; and $\tau = 2L/c$ is the round trip time in the external cavity section. The lasing condition should now be expressed as: $\alpha l = \exp \{(g - \alpha)l - i2nk\lambda\} = 1$, where $r_1$ is the reflectivity of LD chip rear facet; $l$ is the length of chip. Both of gain $g$ and index $n$ are functions of frequency $\omega$, carrier density $N$, and photon number $P$, and of junction temperature as well. In the laser with a cavity composed of grating feedback external cavity and internal semiconductor F-P cavity, the grating not only modifies gain spectrum, but also induces frequency-related phase shift at reflection. Offset between gain peak $\omega_{g0}$ and cavity resonance $\omega_0$ decides the operating mode; and causes also mode hopping, as analyzed in [9].
Very few papers on instability analysis have involved the influence of transverse modes. Ref. 10 analyzed bifurcation in VCSELs due to multi-transverse-mode subject to weak external feedback. Although most diode laser chips are designed and fabricated for the fundamental transverse mode, they may get into multiple transverse mode states transiently. It is conjectured that the carrier distribution might be disturbed to deviate from its stable state at L-I kinks. L-I curve kink phenomena were observed earlier [11], and were explained to originate from transverse gain depletion or gain profile deformation [11,12], which may result in higher order transverse modes, and in mode competition as well. Ref. 13 described spectra of a multi-transverse mode diode laser, showing a typical mode spacing of 0.018nm between the first order and fundamental transverse modes, which is about one tenth of the longitudinal mode spacing; and a theory based on a model of Hermite-Gaussian transverse mode was given. A detailed analysis is given in Ref. 14. Since index in semiconductor is a function of carrier density, the carrier distribution variation will lead to a change of effective index and the resonance frequency \( \omega_b \) too. The experimental results of this paper indicate that the effect of transverse modes should be taken into consideration in understanding the chaotic instability.

The junction voltage jump may be a new observed phenomenon. Ref. 15 described voltage change in self-coupled diode lasers, which was induced by external feedback but in stable output state. As well known, junction voltage is a function of temperature, but the transition observed in this work is so fast that it can hardly be explained by temperature change in the active region. The injection current was monitored to be stable with variation below 1\( \mu \)A, so the voltage jump can not be attributed to the current. A constant current means a stable injected rate of electron number, whereas increasing of output photons should imply decreasing of total electron number in the active volume due to stimulated recombination. On the other hand, junction voltage is usually an ascending function of carrier density. So usually a higher output power means a lower junction voltage when the injection current is fixed. Therefore the observed phenomena shown in Fig. 7 and 8 seem contradictory with what is mentioned above.

Ref. 15 proposed mechanisms to explain the voltage change with the feedback. One of them is the photoconduction effects by the return beam irradiating the active region and its vicinity, which would lower the series resistance, and thus the voltage. In our ECDL, transiently varied transverse mode distribution induces an expanded near field distribution, and a larger irradiated area surrounding the active region, which will lower the voltage due to the photoconduction, and perhaps the photovoltaic effect as well. On the other hand it causes a lower feedback coupling coefficient and a lower output power. The accompanied voltage jump found at self pulsation state may provide internal information on mechanism of the chaotic instability. More work is surely needed to get an exact and detailed explanation for the phenomena.

4. Conclusion

In conclusion, results of experimental study on chaotic instabilities in a grating external cavity diode laser with Littman configuration are presented in the letter. Peculiar behaviors of self-pulsation are described, showing complicated chaotic features at the L-I kinks. Spectral characteristics and far-field patterns are recorded for different output level, which can be attributed to competitions of longitudinal modes and variations of transverse mode distribution. It is observed that junction voltage jumps in the same pace with the output power, which may provide more information to explain observed chaotic instabilities.

It is required in practical applications that the ECDL can work stably in a large output range and a large tunable frequency range; and the instabilities should be avoided as far as possible. The observed phenomena presented in this letter may provide information not only for understanding internal mechanisms of the chaos, but also for improving ECDL performances practically. Further work should be done both on theoretical simulation and more experimental observations.