Dynamics and pulse-package oscillations in broad-area semiconductor lasers with short optical feedback

Akira Takeda,¹ Rui Shogenji,² and Junji Ohtsubo²,a)
¹Graduate School of Engineering, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8561, Japan
²Faculty of Engineering, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8561, Japan

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Pulse-package oscillations in broad-area semiconductor lasers subjected to short optical feedback are experimentally observed. The pulse-package oscillation consists of a frequency component that corresponds to an external optical feedback loop with an envelop of periodic low-frequency fluctuations. However, the periodicity induced by optical feedback does not always improve the time-averaged near-field beam profiles in relation with the optical feedback dynamics. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4769181]

Broad-area semiconductor lasers are promising light sources for various industrial applications since they have a much higher electrical-to-optical power conversion efficiency than other lasers. However, they are unstable even in solitary operation due to the spatial dependence of the laser oscillations along the stripe width. The instability in the dynamics of broad-area semiconductor lasers is a filamentation phenomenon.¹–⁶ Filamentations greatly reduce the quality of the laser beam, including the time-averaged beam profile and the laser coherence. The dynamics of broad-area semiconductor lasers with optical feedback have been extensively studied⁶–¹⁶ since the effects of optical feedback are crucial for applications such as material processing and they can cause laser damage. Optical feedback effects can also be used to shape the beams of broad-area semiconductor lasers.⁶,¹²–¹⁶

A typical phenomenon exhibited by semiconductor lasers with optical feedback is low-frequency fluctuations (LFFs). In short optical feedback regimes, pulse-package oscillations, which consist of a frequency component of the external optical feedback loop modulated by periodic LFFs, have frequently been observed in conventional narrow-stripe edge-emitting semiconductor lasers and vertical-cavity surface-emitting semiconductor lasers.¹⁷,¹⁸ LFFs have also been observed in broad-area semiconductor lasers with optical feedback.⁸ Mandre et al.⁹ observed pulse-package oscillations in a broad-area semiconductor laser with short optical feedback. However, they used filtered optical feedback and the RF spectrum of the pulse-package oscillations differed from those observed in narrow-stripe edge-emitting semiconductor lasers. Despite the importance of the effects of optical feedback for broad-area semiconductor lasers, their dynamic characteristics have been insufficiently characterized. Like the microscopic dynamics, the characteristics of the time-averaged beam profiles, which is related to these fast spatio-temporal oscillations, are very important for applications. The time-averaged beam profile of broad-area semiconductor lasers is strongly affected by filamentations, LFFs, and fast chaotic oscillations.¹¹

In this study, we investigate the dynamics of broad-area semiconductor lasers with short optical feedback. Here, the term “short” indicates that the external mirror is positioned at less than the length corresponding to the laser relaxation oscillation frequency. In this region, we experimentally observed pulse-package oscillations. In a previous study,¹¹ we observed pulse-package oscillations of periodic filaments modulated by a short external optical feedback loop. However, the pulse-package oscillations observed in the present study differ from those oscillations. The pulse-package oscillations observed in the present study consist of a frequency component of the external optical feedback loop modulated by periodic LFFs. They are commonly observed in narrow-stripe edge-emitting semiconductor lasers.¹⁷ This study seeks to demonstrate the existence of pulse-package oscillations in broad-area semiconductor lasers and to determine the relation between pulse-package oscillations and the quality of the time-averaged beam profiles. The present results reveal that the periodicity induced by optical feedback does not always improve the time-averaged beam profiles.

In the experiments, we used a Sony SLD301V gain-guided broad-area semiconductor laser with an AlGaAs quantum-well structure (oscillation wavelength: 780 nm; maximum output power: 100 mW). The active region was 50 μm wide and the threshold injection current $I_h$ was 127 mA. In the solitary state, the laser oscillated with multiple modes (both longitudinal and lateral modes). We used a gain-guided laser, which is less stable than an index-guided laser; however, both lasers exhibit similar macroscopic instabilities for both solitary and optical feedback oscillations.¹ The laser usually oscillated at about three oscillation lines in solitary mode and the transverse modes had a spectral separation of 0.315 nm. The laser was the same type used in the previous experiments and its spectrum was almost the same as that in Fig. 2(b) in Ref. 8. The sub-modes were 5–10 dB less intense than the main mode. Both the main mode and sub-modes were simultaneously detected in the experiment. A stabilized current source driver controlled the bias injection current of the laser while an automatic temperature control circuit was used to set the laser temperature. The light emitted from the laser was collimated by two cylindrical lenses.¹¹

¹¹Electronic mail: tajohts@ipc.shizuoka.ac.jp.
The beam was split by a partial mirror and one portion was fed back to the active layer. In the present experimental configuration, the minimum distance between the external mirror and the laser facet was 4 cm. The external optical feedback length $L_{\text{ext}}$ was varied between 4 and 20 cm.

We defined the delay time due to optical feedback as $\tau = 2L_{\text{ext}}/c$ (where $c$ is the speed of light in vacuum). Several optically coated dielectric mirrors were prepared; the feedback strength could then be varied using mirrors with different reflectivities. We examined the dynamics for fixed external mirror reflectivities of 1%, 4%, 10%, and 20%. The light transmitted through the partial mirror was fed into diagnostic systems. The beam was detected by a high-speed photodetector (New Focus, 1554A; bandwidth: 12 GHz) and the photocurrent from the detector was analyzed by a fast digital oscilloscope (Agilent, Infiniium DSO 80804B; bandwidth: 8 GHz; sampling rate: 40 GSample/s). A CCD camera was used to capture the time-averaged near-field pattern.

Figure 1 shows an example of pulse-package oscillations in the broad-area semiconductor laser for a bias injection current of 140 mA ($1.1I_{\text{th}}$). The external cavity length is $L_{\text{ext}} = 8$ cm and the external mirror reflectivity is 20%. The laser has a relaxation oscillation frequency of 1.1 GHz at this bias injection current, which corresponds to a length of 13.6 cm, demonstrating that the assumption of short optical feedback is valid. Figure 1(a) shows the spectrum of pulse-package oscillations for a full bandwidth of DC-8 GHz (the lower half of the spectrum is shown). The main spectral peak is at the external loop frequency of 1.88 GHz and the lower small peak at 0.4 GHz corresponds to periodic LFFs. Side peaks of LFFs are also visible near the external loop frequency of 1.88 GHz. The observed RF spectrum is similar to that obtained by Heil et al. for conventional narrow-stripe edge-emitting semiconductor lasers.17 Figure 1(b) shows the low-pass-filtered time series with a 3-dB bandwidth of 2.5 GHz. Here, we used a low-pass filter to enhance the visibility of the fundamental periodicities since the whole spectrum included their higher harmonics, as the spectrum in Fig. 1(a) clearly shows. There are periodic oscillations with frequencies of about 2 GHz inside the periodic LFF envelope of about 0.4 GHz. The time-averaged near-field beam profile is plotted in Fig. 1(c) for this condition. The beam profile can be compared with that of the solitary oscillation shown in Fig. 3(a). We discuss the quality of the time-averaged beam below; however, we note that the periodicity of pulse-package oscillations does not improve the time-averaged near-field beam profile, as shown in Fig. 1(c).

Figure 2 shows LFF oscillations for a different external cavity length of $L_{\text{ext}} = 20$ cm and an external reflectivity of 10%. The bias injection current remains the same at $1.1I_{\text{th}}$. Since the relaxation oscillation length is 13.6 cm, the feedback corresponds to the long feedback regime. Typical LFF oscillations such as those in Fig. 2 were observed in the long optical feedback regime irrespective of the feedback strength of the external mirror. Figure 2(a) shows the RF spectrum. The spectrum contains a spectral peak corresponding to an external cavity frequency of about 750 MHz and its higher harmonics; however, the LFF component is not apparent in this spectrum. The LFF frequency is determined to be 40 MHz from the expanded spectrum for the lower-frequency component. Figure 2(b) shows a time series for a bandwidth of 8 GHz. This waveform exhibits LFF-like oscillations. The LFF oscillation frequency is estimated to be about 40 MHz. For higher mirror reflectivities of 10% and 20%, the laser generally exhibits pulse-package oscillations when the external mirror was positioned within the length corresponding to the relaxation oscillation frequency (i.e., in the short optical feedback regime). In contrast, the laser exhibited normal LFF oscillations such as those in Fig. 2 in the long optical feedback regime. For a mirror reflectivity of 4%, the laser
output consisted of both conventional LFFs and pulse-package oscillations so that pulse-package oscillations were not clearly observed. For the lowest reflectivity of 1%, pulse-package oscillations were hardly observed, even in the short optical feedback regime; instead, fast chaotic oscillations with a dominant frequency close to the relaxation oscillation were mainly observed. Figure 2(c) shows the time-averaged near-field pattern. The side peaks are slightly suppressed relative to those of the time-averaged near-field intensity of the solitary oscillation; however, the order of the main spatial mode remains the same (the second-order mode is the dominant spatial mode for the solitary oscillation, as shown in Fig. 3(a)).

As mentioned above, the periodicity induced by regular pulse-package oscillations does not improve the time-averaged near-field profile for applications (Fig. 1(c)). We next investigated the dependence of the time-averaged beam profile on the external mirror length. Figure 3 shows time-averaged near-field patterns for various external cavity lengths. Figures 3(a)–3(c) show the results for a bias injection current of 1.1$I_{th}$ and an external cavity reflectivity of 10%, and Figs. 3(d)–3(g) show those for a bias injection current of 1.5$I_{th}$ (190 mA) and an external cavity reflectivity of 20%. The second-order spatial mode is the dominant mode for the solitary oscillation at 1.1$I_{th}$ (Fig. 3(a)). However, higher spatial modes are excited for a short external cavity length of 7 cm (Fig. 3(b)). The third-order mode is the main spatial mode in Fig. 3(b). Therefore, the instability is further enhanced for this external cavity length. Under this condition, the time series exhibits pulse-package oscillations similar to those in Fig. 1(b). Increasing the external cavity length to $L_{ext} = 20$ cm (Fig. 3(c)), which corresponds to long external cavity feedback, the beam profile is slightly improved compared to that of the solitary oscillation. The laser exhibits common LFF oscillations at this external cavity length. At a bias injection current of 1.5$I_{th}$, the relaxation oscillation frequency is 2.0 GHz and the corresponding external cavity length is 7.5 cm. The fifth-order mode is the main spatial mode of the solitary oscillation in Fig. 3(d). Higher spatial modes are excited for short optical feedback of $L_{ext} = 6$ cm in Fig. 3(e), while the main spatial mode has the same order as the solitary oscillation. Similar results were obtained for numerical simulations based on the rate equations for broad-area semiconductor lasers with short optical feedback (results not shown). Higher spatial modes generally tend to be excited with the increasing external cavity length. The near-field pattern changes drastically at a slightly longer external cavity length of $L_{ext} = 8$ cm (Fig. 3(f)). The intense peaks at both edges in the solitary oscillation are greatly suppressed and the lower spatial modes are excited by the optical feedback. This external cavity length is almost equal to the length of the relaxation oscillation frequency. Further increasing the external cavity length to $L_{ext} = 17$ cm (Fig. 3(g)) causes the side peaks to grow again and higher spatial modes to be excited. The time-resolved waveforms in Figs. 3(e)–3(g) are not LFFs, but they all exhibit fast chaotic oscillations since the laser was biased well above the threshold.

We experimentally observed pulse-package oscillations in broad-area semiconductor lasers with short optical feedback. Pulse-package oscillations are universal phenomena that are observed in any kind of semiconductor laser. Pulse-package oscillations are generally observed for relatively strong optical feedback with a lower bias injection current close to the threshold. This is one of the main results in this study. The other important result is the great enhancement of higher spatial modes when pulse-package oscillations occurred. Consequently, the periodicity induced by regular pulse-package oscillations does not improve the time-averaged beam profile of broad-area semiconductor lasers. We conducted numerical simulations for the experiments using rate equations and obtained similar trends (results not shown). It is important to study the spatiotemporal dynamics of broad-area semiconductor lasers with optical feedback for both fundamental research and applications.