Mode-Locking in Broad-Area Semiconductor Lasers Enhanced by Picosecond-Pulse Injection

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***Abstract*—We present combined experimental and theoretical investigations of the picosecond emission dynamics of broad-area semiconductor lasers (BALs). We enhance the weak longitudinal self-mode-locking that is inherent to BALs by injecting a single optical 50-ps pulse, which triggers the output of a distinct regular train of 13-ps pulses. Modeling based on multimode Maxwell–Bloch equations illustrates how the dynamic interaction of the injected pulse with the internal laser field efficiently couples the longitudinal modes and synchronizes the output across the laser stripe. Thus, our results reveal insight into the complex interplay between lateral and longitudinal dynamics in BALs, at the same time indicating their potential for short optical pulse generation.**

***Index Terms*—Broad-area semiconductor lasers (BALs), mode-locking, picosecond pulses, semiconductor lasers, spatiotemporal dynamics.**

I. Introduction

BROAD-AREA semiconductor lasers (BALs) are edge-emitting semiconductor lasers with an extended width of the emitting area of typically 50–200 μm to obtain high output powers of several watts. Their emission is dominated by a multitude of complex phenomena ranging from static beam filamentation, regular pulsations, and laterally migrating filaments to irregular, chaotic spatiotemporal dynamics on nano- and picosecond timescales [1]–[5]. This is associated with the excitation of multiple longitudinal and lateral modes, which typically cover a spectral width of 1–2 nm. These phenomena are a consequence of the extended resonator geometry and the highly nonlinear interaction of the intense optical field with the semiconductor gain medium.

Motivated by the perspective of widening the field for BALs in high-power applications, most of the recent efforts have been focused on an improvement of their extremely poor spatial and temporal coherence. Comprehensive strategies have been pursued to control the complex emission dynamics and to generate spectrally narrow, preferably single-mode operation by means of optical injection [6]–[8] or feedback [9], [10]. In contrast to that, it might also be beneficial to exploit the strong intrinsic nonlinearities. In particular, mode-locking of the multiple longitudinal modes—a subject which has in many aspects attracted extensive interest ever since the breakthrough of the semiconductor laser [11]–[19]—could lead to applications of BALs in short optical pulse or high repetition rate signal generation at high powers.

In addition, fundamental questions arise from the fact that the BALs emission does not only consist of many longitudinal modes, but each of these modes consists in fact of a multitude of different lateral modes typically up to the tenth order. This allows for a variety of phenomena associated with locking of the various modes: lateral modes of different longitudinal order or different lateral modes within the same longitudinal mode order might couple. In addition, coexistence of partial mode-locking of lateral and longitudinal modes might occur. Thus, important questions include: in which way does mode-locking actually occur in BALs and how do the lateral modes contribute? Is it possible to control and enhance in particular longitudinal mode-locking to obtain a picosecond pulse source? The answers to these investigations provide basic insight into the interplay between longitudinal and lateral modes and into the complex nonlinear spatiotemporal interactions of BALs.

In this paper, we demonstrate that weak self-mode-locking typically occurs in free-running BALs and manifests itself in fast regular intensity pulsations of the emitted light at the cavity roundtrip time. It can be substantially enhanced to almost completely pulsed emission across the entire width of the laser. We achieve this by injection of a single optical 50-ps pulse into the BAL, which initiates the output of a sharp regular train of 13-ps short optical pulses persisting for about 100 cavity-roundtrips. These investigations are extended by numerical modeling based on multimode Maxwell-Bloch equations. From the modeling, we can explain how the propagating injected pulse is able to enhance and stabilize the mode-locking by dynamically coupling the different longitudinal modes. The calculations also show the destabilizing influence of the lateral modes and spatial interactions which finally reduce the strong longitudinal mode-locking, giving rise to the formation of laterally migrating filaments as before the optical injection.

II. Experimental Results

The measurements have been performed using a standard BAL with a quantum-well active area emitting at a wavelength around 800 nm with a stripe width of 100 μm and a cavity-length of 2 mm. The front facet of the BAL is imaged onto the entrance slit of a single-shot streak camera, which detects laterally and temporally resolved nearfield images of the output intensity with a temporal resolution of 5 ps. Details of the streak camera setup can be found in [4]. Fig. 1 depicts a 1.6-ns long streak image of the solitary BAL operated at

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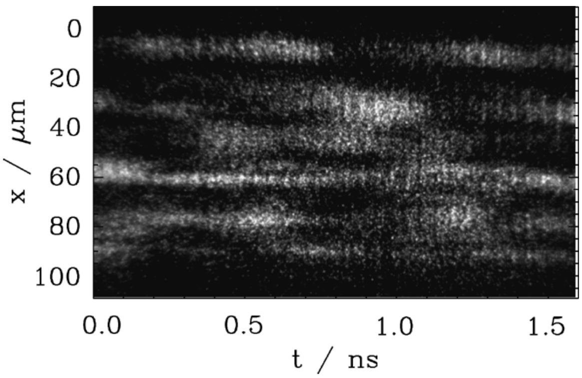

Fig. 1. Streak camera image of the nearfield emission of the free-running laser.

1.5 I_{th} (threshold current $I_{th} = 525$ mA). The vertical axis of the image displays the lateral position on the laser facet, while the horizontal axis shows the temporal evolution of the emitted intensity. We observe the well-known filamentation and the existence of lateral instabilites and laterally migrating filaments on timescales of a few hundred picoseconds. This dynamical behavior has been reported before and is explained by coupling of lateral modes due to an interplay between spatial holeburning, self-focusing and diffraction [4].

In addition to the dynamics on timescales of a few hundred picoseconds, the laser exhibits a fast regular intensity modulation. The modulation period of 54 ps (18.5 GHz) corresponds to the longitudinal mode separation of 0.04 nm in the 2-mm-long cavity. It indicates the existence of partial self-coupling of the longitudinal modes in these devices. The formation of the lateral dynamics as well as the fast intensity pulsation has also been found and explained in numerical modeling of BALs [20]. It is a particular consequence of the spatially extended active medium of these lasers along with the various timescales of propagation and spatial holeburning. Thereby, we find in particular that the occurence of the lateral instabilities in the BAL supports the formation of the longitudinal mode-locking.

In general, we have observed this kind of moderate intensity pulsation at the cavity roundtrip period in many BALs, therefore, being one of their distinct emission features. This is in contrast to conventional solitary narrow stripe emitters were self-mode-locking in free running operation to our knowledge is usually not observed, with the exceptions of degraded devices containing regions of saturable absorption [12] or, as recently reported, in a quantum cascade laser exhibiting giant nonlinearity [18].

In the following, we concentrate on the fast round-trip pulsation. Therefore, we analyzed the emission in the shortest accessible time window of 620 ps allowing the highest temporal resolution. This is shown in Fig. 2(a). The fast round-trip modulation at 54-ps repetition rate becomes even more apparent in the spatially integrated time series depicted in Fig. 2(b), which has been obtained from Fig. 2(a) by numerically integrating the intensity across the whole stripe width. To enhance the formation of the intensity pulsation, we additionally inject an optical picosecond pulse into the BAL and investigate its propagation and its impact on the emission. For this, a wavelength-tunable (around 800 nm), 7-nm-wide, 150-fs pulse from a Ti:sapphire-laser is used.

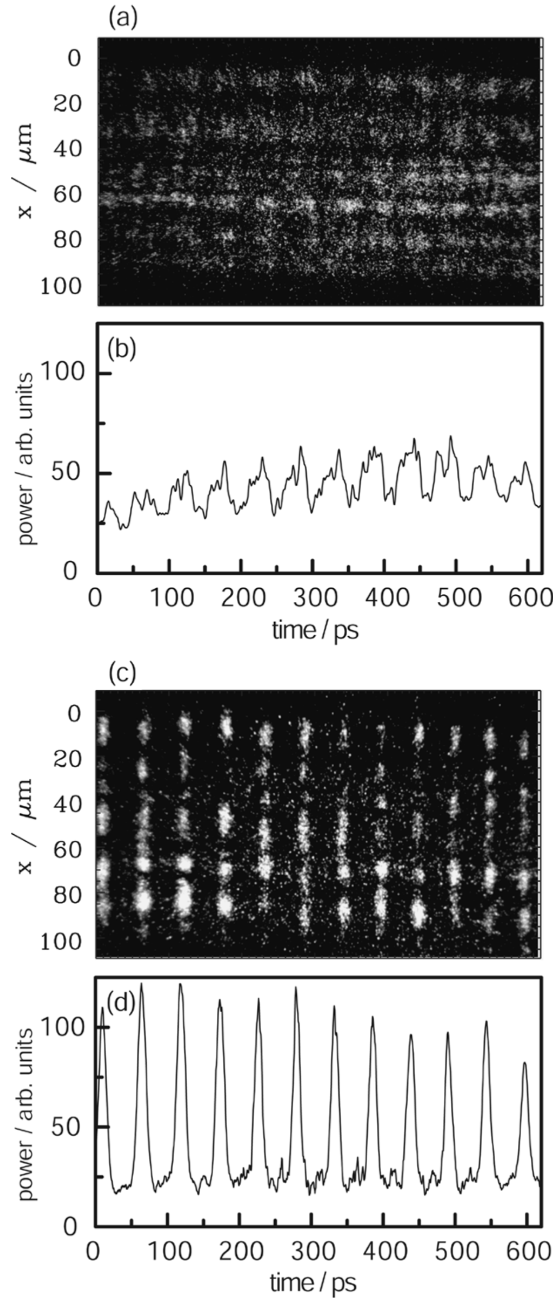

Fig. 2. Streak camera images of (a) the nearfield emission of the free-running laser and (c) several nanoseconds after injection of the optical pulse; (b) and (d) show the corresponding spatially integrated output power versus time.

It is sent through 25 m of optical single-mode fiber, which temporally broadens it to about 50 ps, and is injected via a focusing lens into the BAL through the rear facet, while the emission from the front facet is again imaged onto the streak camera. The energy of the injected pulse inside the BAL is roughly estimated to 20 pJ, which means that its peak power is comparable to, or slightly larger than the power of the solitary BAL's emission. The impact of the injected pulse is considerable. First, it excites relaxation oscillations, which are damped after a few nanoseconds. At the same time, however, the injection of the Ti:sapphire pulse changes the emission of the BAL from the moderately modulated continuous wave (CW)-operation of Fig. 2(a) to almost completely pulsed output. The pulses persist even after the

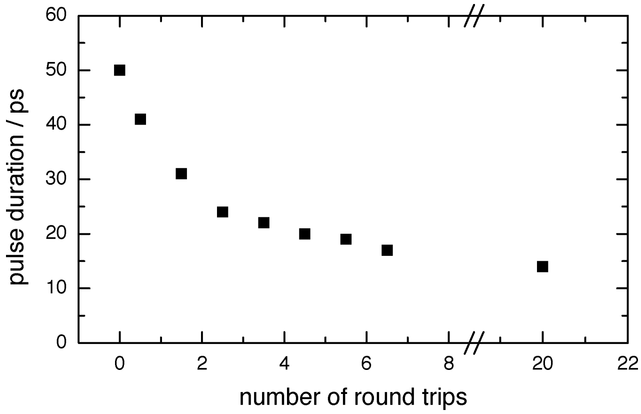

Fig. 3. Evolution of the pulse duration after injection of the 50-ps pulse as function of the number of cavity-roundtrips. The value of 13 ps plotted after the axis break is the finally stable pulsewidth which persists for several nanoseconds.

relaxation oscillations have been damped. This situation is depicted in Fig. 2(c) and (d), which shows the emission of the BAL about 2 ns after the pulse injection. The streak image [Fig. 2(c)] shows that the pulsed emission is not confined to a restricted region of the laser. In spite of pronounced lateral intensity variations, which indicate strong beam filamentation, the pulses are, in fact, perfectly synchronized across the entire laser stripe, resulting in the high output peaks in the spatially integrated plot in Fig. 2(d). The pulse duration amounts to 13 ps with an energy of several picojoules. The consecutive pulses have a repetition period of 54 ps.

Analyzing streak-camera images which are taken beginning at the time of the injection of the external pulse, we are able to follow the formation of the final 13-ps pulsation from the initial injection of the 50-ps pulse. The evolution of the pulse duration for consecutive roundtrips is plotted in Fig. 3. We remarkably find that the initial pulse shortens during the first roundtrips until it reaches its final value of 13 ps. We should note that neither the shortening nor the finally stable 13-ps pulses can be explained simply by dispersion compensation of the injected pulse due to the semiconductor group velocity dispersion (GVD). The injected pulse is indeed strongly chirped after propagation through the fiber. However, the GVD of the BAL has been determined to be $\lambda\, d^2n/d\lambda^2 = 4 \pm 1\ \mu\mathrm{m}^{-1}$. It has the same sign as the fiber dispersion and cannot compensate the initial chirp. Therefore, we interpret the results as a successive enhancement of the longitudinal mode-locking as the injected pulse dynamically couples the longitudinal modes of the BAL while propagating. It is worth noting that the establishment of the final 13-ps pulse train is fairly insensitive to the position and angle of the initial pulse injection and it also works when the center wavelength of the pulse is tuned about 10 nm away from the solitary BAL's emission wavelength. This indicates that the coupling of the injected pulse to the laser modes is rather a dynamic process than an initial coherent preparation. It requires a few roundtrips for building up the locking of all the modes. The high modulation depth and the small duration of the pulses—13 ps is a reasonable value for a semiconductor laser without having additional subsequent chirp compensation—imply that almost perfect mode-locking is achieved under these conditions.

For support of this interpretation and to gain insight into the physical mechanisms, we perform numerical simulations of the BAL dynamics under optical picosecond pulse injection.

III. Modeling Results and Discussion

In recent years, numerous models have been set up to describe and simulate the behavior of semiconductor lasers. Listed in order of increasing complexity, these are: phenomenological rate equations for the (spatially homogeneous) carrier and photon dynamics, semiclassical laser theory on the basis of Maxwell-Bloch equations for the spatio-temporal dynamics of the optical fields and the electron-hole plasma, and quantum theoretical descriptions of the full light and matter dynamics in the semiconductor laser with consideration of quantum fluctuations. The advantage of the semiclassical Maxwell-Bloch theory is the spatially and temporally resolved description of the coupled light-matter dynamics. This theory provides, in particular, a systematic inclusion of all physical processes relevant in a given material system and of nonlinear effects with their respective characteristic interaction lengths and time scales ranging from femtoseconds up to nanoseconds.

The numerical results presented in this paper are based on the semiclassical laser theory, which is appropriate for a realistic description of physical properties (e.g., temporal dynamics, spatial and spectral beam quality) of spatially extended semiconductor lasers. The simulations on the coupled spatiotemporal light-field and carrier dynamics in the BAL use an effective multimode Maxwell-Bloch approach [21]. The multimode Maxwell-Bloch equations consist of coupled spatio-temporally resolved wave equations for the counterpropagating light fields including propagation, diffraction, and longitudinal mode dynamics and two-level Bloch equations for the dynamics of the carriers. The dynamic spatio-temporal interplay of longitudinal modes that typically affects the emission dynamics of BALs is included via a multimode expansion of the fields. Due to the explicit inclusion of longitudinal modes and the consideration of transverse light field and carrier dynamics, the model allows the self-consistent inclusion of the coexistence and the interaction of many transverse and longitudinal modes responsible for the complex light field and mode dynamics. We would like to note that our model is not appropriate for the simulation of microscopic carrier effects such as carrier-heating, highly nonlinear carrier distributions, phonon dynamics, or many-body effects. A suitable description of these phenomena which is beyond the scope of the paper would require a microscopic description [21].

The parameters of the laser structure were taken in accordance with the experimental values as far as they were accessible. These are wavelength, cavity length, width, index-guiding, and mirror reflectivities. For the remaining laser parameters we have taken reasonable values. This allows for a qualitative explanation of the observed effects, whereas quantitative reproduction of details of the spatio-temporal emission dynamics is beyond the scope of this paper.

Fig. 4 displays in two time-traces the calculated nearfield dynamics of the optically injected BAL. In the simulations the injection of the light pulse, which has in this case been assumed unchirped, and had a pulse duration of 50 ps, was realized via the

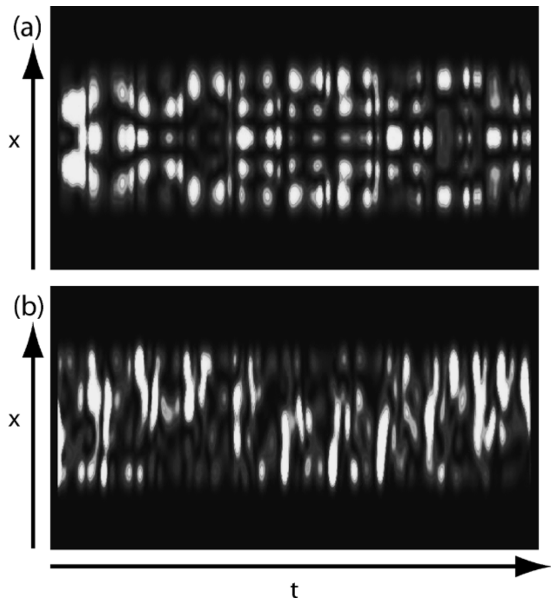

Fig. 4. Modeling results of the spatiotemporal nearfield emission dynamics of the BAL after optical pulse injection. In analogy to the experimental streak camera images, the horizontal axis shows time and the vertical axis the lateral position on the laser facet. Both images display 1000 ps of the time evolution, (a) starting 200 ps and (b) 3200 ps after pulse injection. The lateral width of the emission is approximately 100 μm.

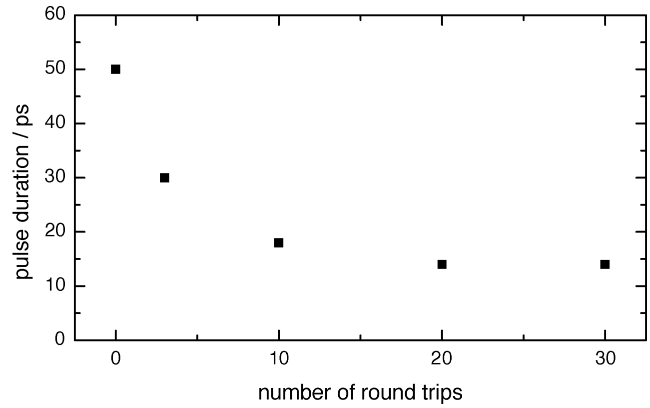

Fig. 5. Calculated evolution of the pulse duration after injection of the 50-ps pulse as function of the number of cavity-roundtrips.

boundary conditions of the wave equations. Figs. 4(a) and (b) show the dynamics of the emitted light fields in a time window of 1000 ps, respectively. The plots visualize the buildup and decay of a longitudinal mode-locking: in the first time-trace [Fig. 4(a)], 200 ps after the injection, the injected light pulse starts its dynamic interaction with the laser-internal light field. After a few roundtrips in the active area, the pulse has established a synchronization of the complex transverse light-field dynamics of the free-running laser leading to the formation of regular pulses with a lateral light field distribution that extends over the whole width of the laser, comparable to the experimental result shown in Fig. 2(c). The periodicity of the emitted light pulses thereby corresponds to the roundtrip time in the BAL. The periodic intensity modulations that can be seen in the free-running laser thus are triggered by the propagating light pulse leading to locking of the longitudinal modes.

In the second time window, starting 3200 ps after the injection of the light pulse, the transverse light pattern has changed significantly. A complex transverse light field dynamics arises leading to asymmetric intensity patterns. The amplitude of the propagating pulse is reduced by dynamic wave-mixing between the propagating pulse and the laser-internal light fields resulting from the nonlinear interaction with the active charge carrier plasma of the laser medium leading to a decrease in its influence and consequently to a stronger influence of the laser internal dynamics. In this temporal regime, the coupling of the longitudinal modes of the BAL has diminished and the laser emission is characterized by the spatio-temporal light field dynamics characterizing the free-running BAL. As a result, the light field dynamics is now dominated by the mutual interplay of light diffraction, hole-burning, and carrier scattering leading to a complex longitudinal and transverse light field dynamics. In particular, we obtain the transverse dynamics that is typical for the free-running laser: the intensity moves across the laser facet alternating from one side to the other on a slower timescale of several hundreds of picoseconds related to locking of lateral modes. Thus, it qualitatively resembles the experimental streak-image of the free-running laser as displayed in Fig. 1. The duration of the longitudinal mode-locking regime depends on the intensity of the injected light pulse and the injection current in the BAL. Typically, it persists for several nanoseconds, i.e., in the order of 50–100 roundtrips.

The results illustrate the ambivalent effect of the multiple lateral modes of the BAL on the longitudinal mode-locking. On the one hand, it is the lateral extension of the BAL that supports the buildup of the moderate roundtrip pulsation in free running operation, making the pulsation one of the typical features of the emission dynamics of BALs. Moreover, in the regime of strong longitudinal mode-locking after the pulse injection, higher order lateral modes of different longitudinal order are contributing to the longitudinal mode-locking, so that the pulsed emission extends and is synchronized across the entire laser stripe. On the other hand, the lateral width of the laser is finally responsible for a decrease of the pronounced pulsation generated by the pulse injection when lateral modes drop out of the longitudinal mode-locking. This happens due to lateral instabilities and locking of lateral modes of different order within the same longitudinal order. So, finally, the emission is governed by a mixture of partial longitudinal and lateral self-coupling as is typical for free running BALs.

Integration of the light fields at the output facet in transverse direction allows the calculation of the duration of the emitted pulses in dependence of the number of roundtrips. The computational results, which are summarized in Fig. 5, clearly reveal a reduction in pulse duration, indicating the occurrence of longitudinal mode-locking. They confirm the experimental results of Fig. 3. The pulse duration approaches a value of 14 ps, which is similar to the experimentally obtained result. We would like to note that the close agreement between theory and experiment exists although an ideal (unchirped) pulse has been used in the modeling in order to clearly identify mode-locking as the pulse shortening mechanisms. Since the spectral width of the injected pulse in this case is less than the longitudinal mode separation, it cannot simultaneously couple to the numerous longitudinal modes coexisting in the gain spectrum of the BAL. This indicates that the observed mode-locking is a dynamic effect originating from an interplay between pulse propagation and spatio-spectral mode dynamics.

IV. Conclusion

We have investigated longitudinal mode-locking in BALs. These lasers are attractive devices for mode-locking because of their high-power, multiple longitudinal mode operation, and intrinsic optical nonlinearities. The spatial and spectral complexity of BALs leads among other features to a distinct fast pulsation by a partial self-mode-locking in free-running operation already. We have shown, that by injection of an initial optical pulse almost perfect mode-locking across the entire width of the laser resulting in the emission of a 13-ps pulses is achieved over several nanoseconds. Without further control, however, the pulse emission finally decreases and laterally migrating filaments evolve. Thus, we expect that by successive injection of optical pulses synchronized to a suitable subharmonic of the BAL roundtrip time stable picosecond pulse emission over a long time and at high powers should be possible.

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