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Mode locking of lateral modes in broad-area semiconductor lasers by subharmonic optical pulse injection

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We generate stable mode-locking of different lateral modes in broad-area semiconductor lasers (BALs) by local injection of short optical pulses repeated at subharmonics of the lateral mode separation. The locking results in a persistent, periodic spatiotemporal dynamics consisting of a laterally alternating intensity modulation with a repetition rate of 3.4 GHz, which can be regarded as an enhancement and stabilization of the spontaneous dynamic filamentation that is frequently observed in free running BALs. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2185252]

In high-power broad-area semiconductor lasers (BALs), the emission properties are determined by the interplay between the laterally extended waveguide of typically 100 μm width and the nonlinear, local interaction of the intense light field with the semiconductor active medium, in which gain and refractive index are strongly coupled. This gives rise to a broad optical spectrum with a complex mode structure. The emission of BALs usually consists of a multitude of longitudinal but also of lateral (spatial) modes, which can approximately be described as Hermite-Gaussian modes of typically up to 6th–10th order.[1–3] The modes inherently interact with each other within the semiconductor active medium. The interaction leads to a coupling of the longitudinal and the lateral degree of freedom and results in a characteristic spatiotemporal emission dynamics on nano- and picosecond timescales.[4–8] Apart from static filamentation, BALs exhibit in particular laterally migrating filaments, also referred to as dynamic filamentation, and fast round-trip pulsations, which both can be ascribed to partial lateral and longitudinal self-mode locking in these lasers, respectively.[5,8,9] However, the coupling mechanisms are usually not sufficient to establish a complete and stable locking of the modes which would result in a fully developed, periodic emission. Concerning lateral modes, the role of nonequidistant mode separations for the occurrence and stability of self-mode locking, in particular, has been investigated.[9]

Therefore, the question arises in which ways it is possible to influence or enhance mode locking in BALs. This question is not only of fundamental, but also of high technological impact. Establishing perfect mode locking can be used to stabilize and control the complex emission behavior and furthermore lead to applications for BALs as high-power ps pulse sources in optical communication or metrology. In addition, BALs are interesting devices to study mode-locking phenomena from a more fundamental point of view, because of the particular mode structure with the simultaneous existence of longitudinal and lateral modes within the complex, spatially extended laser. Depending on the specific modes which are involved, mode locking can be associated with significantly different emission behavior occurring on different timescales. Pure longitudinal mode locking is associated with fast round-trip pulsations, whereas pure lateral mode locking is associated with (slower) moving filaments on the laser facet. A mixture of longitudinal and lateral mode locking is most likely to occur as it is frequently observed in free running devices, however, only partially established and unstable. Thus, it is not obvious from the start which manifestations of mode locking can occur in BALs and, moreover, whether one type of mode locking can be stabilized to an extent that is necessary for applications.

Recently, we have shown that by injection of an initial short optical pulse into a BAL almost perfect longitudinal mode locking, resulting in the emission of a train of 13 ps pulses which extends in a synchronized way across the whole stripe, can be generated.[10] We have also illustrated how the complete longitudinal mode locking is finally reduced after several nanoseconds when migrating filaments due to lateral self-mode locking, i.e., locking of lateral modes of different order within the same longitudinal order, evolve and a mixture of partial longitudinal and lateral mode locking tends to dominate the emission. The main mechanisms for the partial lateral self-mode locking in BALs have been identified as spatial hole burning, self-focusing, and carrier diffusion.[5,8] Trying to enhance and exploit the lateral mode locking instead of longitudinal mode locking to generate a regular output from BALs might therefore be promising as well. While longitudinal mode locking generates a periodic intensity output with a repetition rate in the range of 20–50 GHz in typical solitary BALs, lateral mode locking should be associated with slower dynamics in the range of 3 GHz corresponding to the smaller lateral mode separation.

For the experiments we have used the same BAL as in the longitudinal mode-locking experiments of Ref. 10. It is a standard commercial BAL emitting around 800 nm with a cavity length of 2 mm and a stripe width of 100 μm. As in Ref. 10 we additionally inject optical pulses of 50 ps duration into the lasing BAL through the rear facet at a repetition rate of 75.3 MHz, i.e., a pulse being injected every 13 ns. The output of the BAL emitted from the front facet is imaged by a synchro-scan streak camera system which is synchronized to the 75.3 MHz rate of the pulse injection. It allows us to measure the spatiotemporal emission of the BAL with a temporal resolution of 10 ps and a simultaneous spatial resolution of 3 μm. In synchro-scan mode the measurements are

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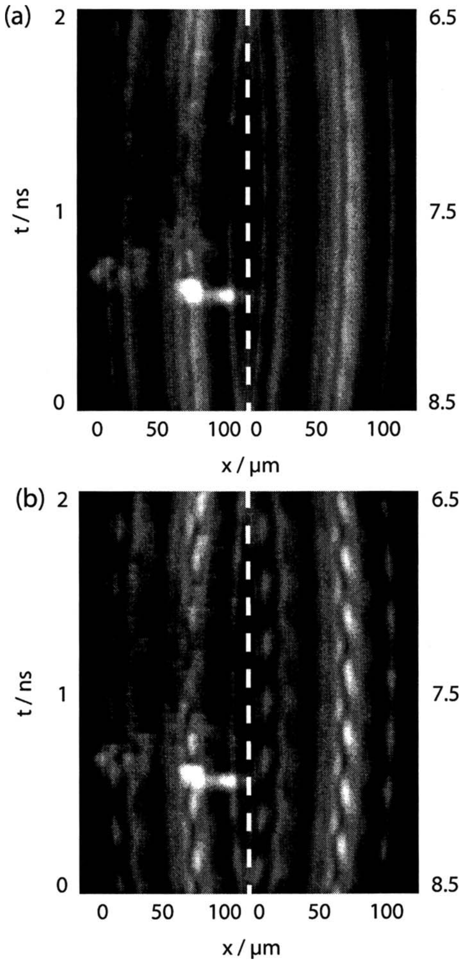

FIG. 1. Synchroscan streak camera images of the emission of the injected laser for a pump current of 670 mA (a) and 680 mA (b). Each image shows two parts of the full sweep within the synchroscan cycle.

repetitively averaged over millions of events, i.e., injected pulses. This means on the one hand that any information about nonrepetitive parts of the emission is lost. On the other hand this method allows us to selectively filter out the emission dynamics repetitively triggered by the injected pulse. Thus, any emission dynamics seen on the synchro-scan images is definitely generated by the injected pulse and is synchronized to its repetition rate.

One has to be aware that in contrast to the more convenient case of longitudinal mode locking, i.e., locking of different longitudinal modes having the same lateral order, which is a purely temporal phenomenon, locking of lateral modes of different order is associated with spatiotemporal dynamics. For example, in an idealized case of locking several Hermite-Gaussian modes with equal frequency separation, the resulting intensity distribution yields a bright spot of intensity moving periodically from one side to the other on the laser facet, while the spatially integrated total intensity remains exactly constant.[11] To adapt the pulse injection in the experiment to the spatially alternating character of this specific output, we inject the pulses locally, with a spot size of about 10 μm on the right hand side of the laser facet and under a small angle tilted toward the center in propagation direction view.

Figure 1 depicts the obtained synchro-scan images of the spatiotemporal emission under pulse injection for two different pump currents (670 and 680 mA). They display the spatial intensity distribution across the laser stripe on the horizontal axis and its time evolution on the vertical axis. Each image consists of two traces, showing the upward sweep on the left and the downward sweep (about 6.5 ns later within the synchro-scan cycle of 13 ns) on the right hand part of each image. The dashed vertical line in the center has been artificially added to the images to indicate the separation between the upward and the downward sweep. The slight bending of the measured traces results from the combined operation of vertical synchro-scan and horizontal blanking unit which is necessary to horizontally separate the upward and downward sweep. The pulses are injected at about $t = 600$ ps on the right hand side of the laser at $x = 80$ μm. Under these conditions one can observe a weak alternating migration of the pulse from one side to the other while it propagates in the laser resulting in a zig-zag like intensity structure on the streak-camera image with a period of about 300 ps. In Fig. 1(a) this lateral migration, however, is barely visible and fades away after about 1 ns. On the backward sweep after 6.5 ns no temporal dynamics remains, and only a spatial intensity variation showing static filamentation across the laser stripe is visible. The situation is remarkably different in Fig. 1(b). Here a distinct, regular spatiotemporal dynamics with a spatially alternating intensity modulation occurs. It persists for the full injection cycle and runs into the next incident of pulse injection after 13 ns without weakening. Thus, under these conditions a durable, fully periodic, spatially alternating emission from the BAL is generated with a repetition rate corresponding to the typical lateral mode separation.

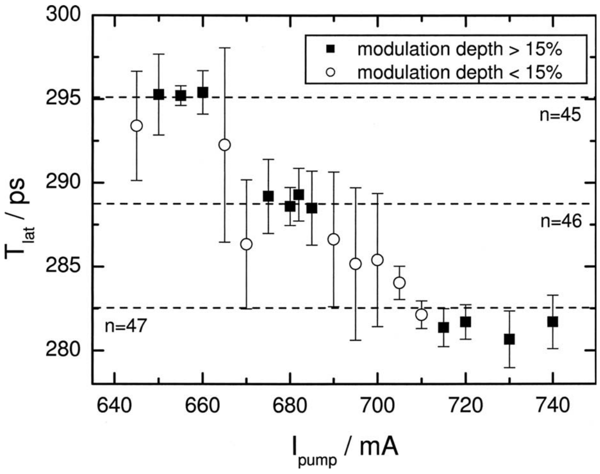

FIG. 2. Period time T_{lat} and modulation depth of the lateral dynamics for different pump currents. The dashed lines correspond to integer fractions of the injection period with integer numbers n.

A possible explanation for the buildup of the stable lateral dynamics in Fig. 1(b) is that here the period of the generated dynamics obviously fits an integer fraction of the period of the pulse injection, so it runs with matching phase into each next pulse injection. Hence, for a systematic investigation we altered the pump current of the laser in small steps and analyzed the output dynamics of the BAL. The results are shown in Fig. 2. It displays the period T_{lat} of the lateral dynamics as a function of the pump current of the BAL. In addition, the modulation depth of the generated dynamics is indicated by the type of the symbol. Full squares show a modulation depth of more than 15% thus corresponding to an emission similar to Fig. 1(b), whereas open circles indicate cases with only weak dynamics such as shown in Fig. 1(a) (in these cases the error bars are quite large as it is difficult to accurately determine a periodicity). As one result, we see that the period of the lateral dynamics tends to drop with growing pump current corresponding to a small increase of the spectral mode separation due to temperature effects with increasing current. More importantly, we find that when the period T_{lat} approaches an integer fraction of the period of the pulse injection (indicated by the dashed line and the corresponding fraction numbers n) at 295, 289, and 282 ps (corresponding to 3.39, 3.46, and 3.54 GHz) strong lateral mode locking with the observed persistent, periodic dynamics occurs. For each harmonic number, there exists a certain locking range, in which synchronization is possible. Thus, we can conclude that indeed stable lateral mode locking is generated by the successive injection of optical pulses at a subharmonic repetition rate into the BAL. This can be considered similar to the experiments, in which stabilization of longitudinal mode locking in passively mode-locked semiconductor lasers[12,13] or generation of longitudinal mode locking in cw lasers[14,15] by subharmonic optical injection has been achieved. As the partial lateral mode locking in free running BALs is mainly caused by spatial hole burning and self-focusing it is quite reasonable that an additionally injected pulse that locally alters the carrier and photon density can enhance and stabilize mode locking if suitably injected.

As mentioned before, lateral mode locking does not generate short optical pulses as longitudinal mode locking does, but rather a periodic spatiotemporal dynamics. However, any additional spatial filtering creates a stable periodic intensity modulation which can be used as a high-repetition-rate optical signal. Finally, we should also note that the value of the harmonic number (n around 45) is quite high, so that we can transform a relatively slow (75 MHz) input signal into a regular 3 GHz signal, which could make the effect promising for potential applications in optical clock recovery.

In conclusion we have demonstrated that mode locking in BALs can be extended to lateral modes. By lateral mode locking we generate a stable, periodic, spatially alternating emission with a repetition rate of around 3.4 GHz in the investigated device. It is created by local, successive injection of optical pulses synchronized to a subharmonic of this repetition rate, which can be current/temperature tuned over a range of a few hundred MHz.

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