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LETTER TO THE EDITOR

Dynamics of modal power distribution in a multimode semiconductor laser with optical feedback

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Abstract
The dynamics of power distribution between longitudinal modes of a multimode semiconductor laser subjected to external optical feedback is experimentally analysed in the low-frequency fluctuation regime. Power dropouts in the total light intensity are invariably accompanied by sudden activations of several longitudinal modes. These activations are seen not to be simultaneous to the dropouts, but to occur after them. The phenomenon is statistically analysed in a systematic way, and the corresponding delay is estimated.

Keywords: Semiconductor laser, multimode dynamics, low-frequency fluctuations, optical feedback

Semiconductor lasers are devices which are very susceptible to exhibiting unstable dynamical behaviour. In particular, when subjected to reflections of their own emitted radiation, they easily enter complex dynamical regimes, exhibiting for instance low-frequency fluctuations (LFFs) in the form of intensity dropouts [1], or fully developed chaotic fluctuations leading to coherence collapse [2]. Most of the related theoretical and experimental studies undertaken so far have dealt with the dynamics of the total emitted intensity [3, 4]. However, the low-cost semiconductor lasers employed in technological applications usually operate in several longitudinal modes. Therefore, analysing the mode dynamics would be necessary, a need which has been recognized only recently [5]. In particular, recent experiments have indeed shown the importance of multimode operation in the LFF regime [6, 7]. Different dynamical [8, 9] and statistical [10] characteristics of this regime have been described in terms of a multimode extension of the well known Lang–Kobayashi model [11].

In the course of the above-mentioned investigations, it was observed that when the feedback was frequency selective (such as that provided by a diffraction grating), the intensity dropouts were accompanied by a sudden activation of other longitudinal modes of the laser [6, 12]. These modes, located at the sides of the main mode (MM) in the gain curve, will be called longitudinal side modes (SMs), in the rest of this letter. The activation of these modes was heuristically interpreted as the mechanism producing the intensity dropouts [12], and was numerically reproduced again by multimode LK models [13, 17]. In this letter, we show experimentally that the side-mode activation also appears in the presence of non-frequency-selective feedback, and that it occurs neither simultaneously nor previously to the intensity dropout, but *after* it. Therefore, one can conjecture in principle that, in this case, this activation cannot be the cause of the dropout event.

Our experimental set-up is shown schematically in figure 1. We use an index-guided single transverse-mode AlGaInP semiconductor laser (RLT6505G), emitting at a nominal wavelength of 650 nm with a threshold current of 20.1 mA, which is controlled with an accuracy of ± 0.01 mA. Its temperature is set to $24.00 \pm 0.01\,^{\circ}$C. The laser output is

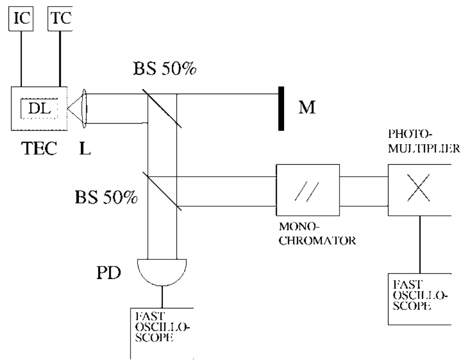

Figure 1. Experimental set-up: DL, laser diode; BS, beamsplitter; M, external mirror; TEC, laser diode mount; PD, photodiode; IC, intensity controller; TC, temperature controller.

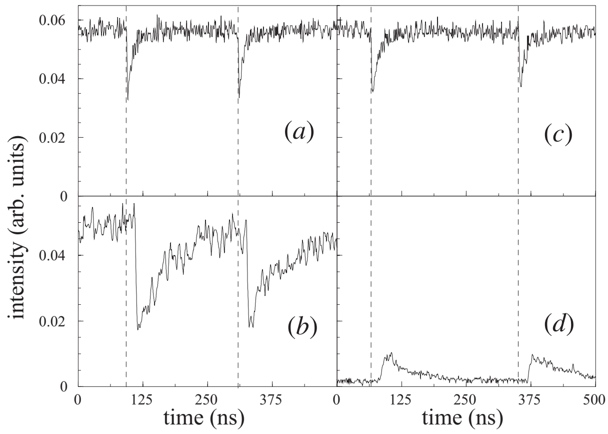

Figure 2. Modal structure of a dropout. Total intensity evolution (*a*), (*c*) compared with that of the main mode of the laser with feedback (*b*) and of the original main mode of the solitary laser (*d*). Traces (*a*), (*b*) and (*c*), (*d*) have been acquired simultaneously (but note the intrinsic delay of the mode-selecting path of the set-up—see text). Vertical dashed lines are a guide to the eye.

collimated by an antireflection-coated laser-diode objective. An external mirror is placed 60 cm away from the front facet of the solitary laser, which corresponds to a feedback time of 4 ns. The threshold reduction due to the feedback is 9.4%. Throughout the paper, the injection current is set to 1.09 times the solitary laser threshold.

Part of the total output intensity is detected by a fast photodiode and sent to a 500 MHz bandwidth HP 54720D digital oscilloscope. The rest passes through a $1/8$ m CVI monochromator with a resolution better than 0.2 nm, used to select the laser modes, and whose output is sent to a Hamamatsu PS325 photomultiplier. The photomultiplier signal is also recorded by the oscilloscope. Note that the time response of the photomultiplier introduces a delay in the mode-selection path ($\sim$20 ns), which will have to be considered when analysing the experimental data, as shown below.

The optical spectrum of our solitary laser shows at least ten active longitudinal modes, with its maximum located at $\sim$658.4 nm and an FWHM of $\sim$0.9 nm. When the feedback is turned on, the spectrum broadens (up to an FWHM of $\sim$1.3 nm), and its maximum becomes shifted $\sim$0.5 nm towards higher wavelengths [14]. For the feedback parameters chosen, mentioned above, the laser emits in the LFF regime. In this regime, we have analysed the dynamical behaviour at different fixed emission wavelengths within the time-averaged optical spectrum of the laser with feedback. We have observed that, while in most of the spectrum the laser exhibits drop-outs simultaneously to the total intensity, a small range of wavelengths exist for which the laser undergoes sudden activations when the total intensity falls. These two opposite behaviours are shown in figure 2, which compares the temporal evolution of the total emitted intensity (traces (*a*) and (*c*) in the figure) with that measured at the maximum-gain wavelength of the spectrum, corresponding to the MM of the laser with feedback (trace (*b*)), and with a smaller wavelength corresponding to a longitudinal SM of the spectrum (trace (*d*)). We stress that these modes are defined in terms of their wavelength position in the time-averaged optical spectrum described above. It can be seen that a power dropout is associated with an abrupt decay of the former and a sudden activation of the latter. Note that the recovery of the MM is much slower than that of the total intensity, a fact that has been already reported in the literature [6, 15, 16]. The activation is seen not to be symmetric, i.e. it does not occur in the other side of the spectrum. Although we display results for the wavelength of the SM of maximum power, the activation and the consequent delay also appear in surrounding wavelengths, which indicates that the phenomenon is quite generic, not restricted to a very specific SM of the laser. Furthermore, we have found similar behaviour in other semiconductor lasers of similar quality, including nearly-single-mode lasers.

We note that, even though the pairs of measurements (*a*), (*b*) and (*c*), (*d*) in figure 2 were acquired simultaneously, the time traces exhibit a systematic delay of $\sim$20 ns between the total-intensity dropouts and the corresponding modal powers (see vertical dashed lines in the figure). This delay is spurious, due to the electronic response time of the photomultiplier used in the mode-selecting path of the experimental set-up (cf figure 1), which is substantially larger than that of the photodiode used to measure the total intensity. However, as we shall show in what follows, a closer inspection of these results reveals that this spurious delay is slightly *larger* for the SM activation than for the MM dropout. Since both of these signals are measured with the same detector, this observation leads to the conclusion that the SM activation does not occur simultaneously with (nor before) the dropout, but *after* it.

In order to estimate the delay between each dropout and its SM activation we proceed as follows. First, several (typically 40) time-trace pairs containing a single total-intensity dropout and its simultaneously measured modal event (either MM dropout or SM activation) are averaged using a predefined event (a given decay of the total intensity in our case) as a trigger. In this way, we average out fluctuations before the dropout event and during the subsequent buildup, and refer all the time traces to a common time origin (given by the predefined event mentioned above). The result of this procedure is shown in figure 3(*a*). One can already see in this figure, which shows several averaged sets for each of the three quantities measured (total intensity, MM intensity and SM intensity), that the SM activation occurs somewhat later ($\sim$1 ns) than the MM dropout (see vertical dashed lines in the figure). In order to identify such a delay more clearly, we compare in figure 3(*b*) the SM signal with the inverted MM one. The delay

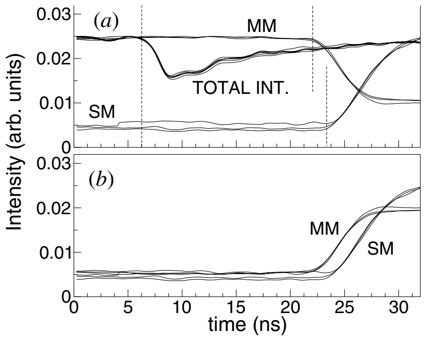

Figure 3. Averaged time traces of a dropout in the total intensity, MM of the laser with feedback and MM of the solitary laser. In plot (*b*), the traces of the MM have been inverted.

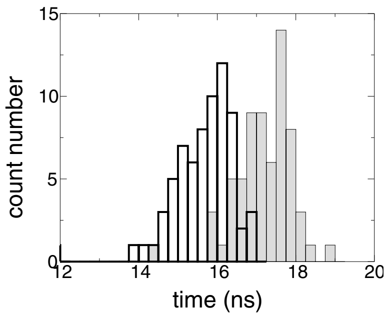

Figure 4. Distribution of times of occurrence of both the dropouts of the MM of the laser with feedback (white bars) and the activations of the SM (grey bars).

now becomes evident. Note also that the escape trajectories of the two modes (from the lasing state in the MM case, and from the off state in the SM case) are basically parallel, which indicates that the instability mechanisms are the same, and hence a direct comparison between them can be made.

We estimate the delay between the dropout and the SM activation as the distance between the two corresponding parallel escaping trajectories, which can be clearly identified in figure 3(*b*) as two distinct sets of straight lines with the same positive slope. We perform a piecewise local linear fit of each of the averaged MM and SM time series, and identify the time instants at which the slope takes its maximum value. Figure 4 represents the distribution of these times, for both the SM activation and the MM dropout, computed from statistics of 3000 dropout events. The distribution functions of these two quantities are clearly separated, with a time difference between their two mean values of 1.5 ± 1.1 ns. Note that the delay in the activation is of the order of the carrier lifetime in this kind of laser, which suggests that the activation is a consequence of the loss of power of the MM of the laser.

In conclusion, we have experimentally observed that LFFs in a multimode semiconductor laser with global (i.e. non-frequency-selective) optical feedback are associated with sudden activations of a longitudinal SM corresponding to the MM of the solitary laser. This extends previous results reporting this behaviour in semiconductor lasers with selective feedback [12, 13], and hence shows that the phenomenon is generic. In our case of non-selective feedback, the activations are seen to occur after the dropouts of the MM of the laser. Assuming that the dropouts in the total intensity and in the MM are simultaneous, one can conclude that the SM activation occurs after the dropout of the total intensity. Therefore, in this case the SM activation cannot account in principle for the destabilization giving rise to the LFF. In contrast, one could conjecture that the SM activations might be a consequence of the loss of power in the MM of the laser with feedback. Work directed at the theoretical modelling of these phenomena is in progress [14].

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