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Abrupt transition from low-coherence to high-coherence radiation in a semiconductor laser with optical feedback

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Abstract: Semiconductor lasers are very sensitive to optical feedback. Although it is well known that coherent feedback lowers the threshold of the laser, the characteristics of the transition from low-coherence radiation—dominated by spontaneous emission—below threshold to high-coherence radiation—dominated by stimulated emission—above threshold have not yet been investigated. Here we show experimentally that, in contrast to the transition that occurs in the solitary laser, in the laser with feedback the transition to high-coherence emission can occur abruptly. We use the speckle technique to show that the transition varies from smooth to abrupt as the amount of light fed back to the laser increases.

1. Introduction

Semiconductor lasers with optical feedback are practical devices that display a rich variety of nonlinear behaviors [1–3]. Optical feedback reduces the laser threshold and can either increase or decrease the coherence of the laser light [4,5]. Since feedback-induced coherence collapse and chaotic dynamics were discovered [6,7], they have been intensively studied and have found non-conventional applications in different areas, including chaos communications, random number generation and reservoir computing [8–11].

Feedback-induced nonlinear regimes in the intensity dynamics, such as low-frequency fluctuations, coherence-collapse, and regime V have been studied in detail —see, e.g., [3] and references therein. However, the effect of optical feedback in the coherence of the emitted radiation during the off-on transition, i.e., from low-coherence radiation below the threshold—dominated by spontaneous emission—to high-coherence radiation above the threshold—dominated by stimulated emission— has not yet been studied to the best of our knowledge.

Widely used techniques to assess the coherence of laser light are based on measuring the width of the optical spectrum, or, in the temporal domain, the second-order intensity correlation function, $g^2(\tau)$. Such techniques allow to detect, well above threshold, the onset of the coherence collapse, which is characterized by a sudden enhancement of the laser linewidth. However, below and near threshold—i.e., during the laser turn-on—the low emitted power and the broad nature of the spectrum make inherently difficult to identify and quantify the effect of optical feedback on the coherence of the emitted radiation.

Here we study experimentally the coherence of the light emitted during the laser turn-on, using a technique based on the analysis of speckle images. With this technique we can quantify the variation of coherence of the emitted radiation using a CMOS camera, without the need of a fast optical amplifier or a fast high-resolution optical analyzer.

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Speckle is a granular, noisy spatial structure produced by the interference of coherent waves [12] that is detrimental in imaging applications [13,14]. However, when laser light propagates in a multi-mode fiber or through a scattering medium, usable information can be obtained from the analysis of the speckle pattern. As an example, optical reservoir computing for prediction of chaotic dynamics has been demonstrated, in which the speckle pattern generated by a scattering medium represents the high-dimensional state of the reservoir [15]. Here we demonstrate that the effect of optical feedback in the coherence of the light emitted during the turn-on is unveiled by the amount of speckle generated, which displays an abrupt increase, reminiscent of a second order phase transition.

2. Experimental setup

The experimental setup, shown in Fig. 1, uses a 653 nm semiconductor laser (AlGaInP multi-quantum well Thorlabs HL6750MG) with threshold I = 41.95 mA. A video of the setup can be found in [16].

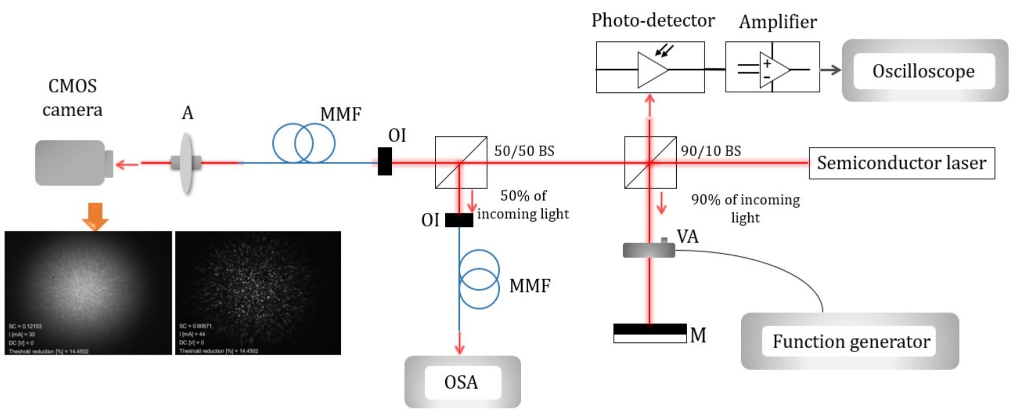

Fig. 1. Experimental setup. A: Manual Attenuator, VA: Variable Attenuator, MMF: Multi-Mode Fiber, BS: Beam Splitter, OI: Optical Isolator, OSA: Optical Spectrum Analyzer. In the second set of experiments, the VA and the mirror were replaced by a diffraction grating.

The laser injected current and temperature are stabilised with an accuracy of 0.01 C and 0.01 mA, respectively, by a Thorlabs ITC502 controller. In all the experiments the temperature was set to 18 C. The laser output intensity is partly fed back to the laser by either an external mirror or by a diffraction grating. In both cases, the length of the external cavity is L_{ext} = 50 cm, which gives a feedback delay time of approximately 3 ns.

When an external mirror is used, the amount of feedback light is electrically controlled by a variable attenuator (VA, Thorlabs LCC1620/M) positioned between a 90/10 beam splitter (BS) and the mirror (M); when a diffraction grating is used, the first order diffraction mode is re-injected to the laser, which is controlled with a Neutral Density Filter (NDF, Thorlabs, GH25-18V).

The VA maximum transmission—about 80%, which provides the highest feedback strength—is obtained when applying to the VA a DC signal of 0 V; the minimum transmission—almost 0%—is obtained for 5 V. The latter will be considered as the solitary laser scenario because the beam coming from the external cavity is almost completely blocked.

It is worth noting that when the diffraction grating is used, only the first order diffraction mode is re-injected. In this diffraction mode the longitudinal modes are spatially separated and therefore, only one is re-injected into the laser—i.e., the feedback from the grating is monochromatic.

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Because the strength of the feedback from the grating is lower than that provided by the mirror, in order to maximize the transmission, we removed the VA from the setup.

The 90/10 beam-splitter (BS) in the external cavity sends light to a photo-detector (Det10A/M Silica based photodetector) that is connected to an amplifier (Femto HSA-Y-2-40) and a 1 GHz digital storage oscilloscope (Agilent Technologies Infiniium DSO9104A) that allows to visualize the temporal dynamics of the laser intensity. A video showing the typical behavior as the current increases can be found in [17].

A second 50/50 BS, placed after the 90/10 BS, divides the beam in two which are coupled to two Multi-Mode Fibers (MMF, Thorlabs M72L02 ϕ = 200 µm, 0.39 NA). Optical Isolators (OI, Thorlabs IO-3D-660-VLP) were placed in front of each MMF in order to avoid unwanted reflections. The first MMF is used to analyze the optical spectrum with an Optical Spectrum Analyzer (OSA, Anritsu MS9710B). Simultaneously, the output of the second MMF is used to analyze the speckle pattern that originates due to the scattering of the laser light in the MMF. The output of the second MMF is imaged onto the sensor of an 8-bit CMOS camera (IDS UI-1222LE-M, pixel size 5.3 µm with a resolution of 1280 x 1024 (h x v) pixels). A manual attenuator (A) is used to adjust the intensity of the light that arrives to the CMOS sensor.

The setup is controlled by a LabVIEW program and the data is processed and analyzed with MATLAB.

2.1. Threshold reduction

The experimental control parameters are the laser's injection current and the amount of light that is fed back to the laser, which is controlled by the VA when the feedback is injected with the mirror. In practice, the feedback strength is quantified by the threshold reduction, $(I^0_{th} - I^f_{th})/I^0_{th}$, where I^0_{th} and I^f_{th} are the threshold currents of the solitary laser—without feedback—and of laser with feedback, respectively. These values are obtained from the light-injection current (LI) curve, shown in Fig. 2(a). The LI curve was measured by placing a Power Meter (Thorlabs PM100A) after the 50/50 BS. We note that the shape of the LI curve is the same for the laser with and without feedback, the only evident effect of the feedback is the lowering of the threshold current—for clarity, the inset shows the LI curve in logarithmic vertical scale, where we see the well-known s-shaped curve.

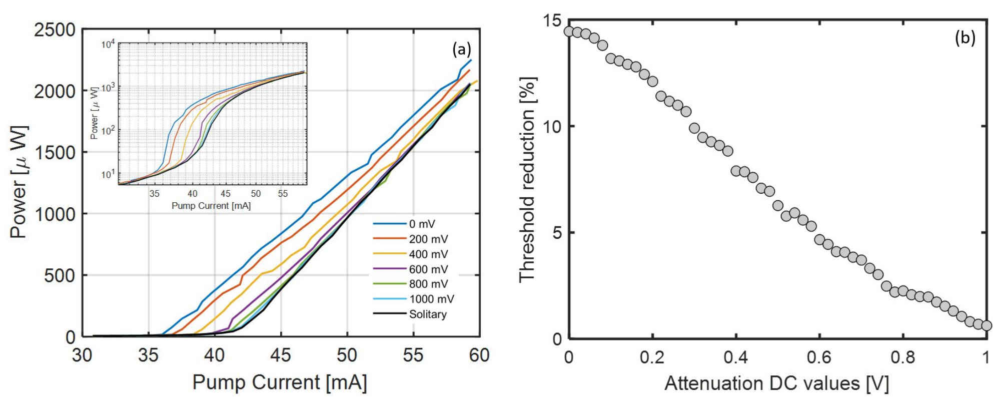

Fig. 2. (a) Light-injection current (LI) curve of the solitary laser and of the laser with different amount of feedback from the mirror—the curves are labeled by the DC voltage in the variable attenuator. The inset shows the LI curve in log-log scale. We observe that the feedback reduces the threshold but does not change the shape of the LI curve. (b) Relation between the threshold reduction, in percentage, and the voltage applied to the variable attenuator.

Figure 2(b) displays the relation between the VA voltage and the threshold reduction. The relation is linear because the relation between the VA voltage and the feedback strength is linear, and the relation between the feedback strength and the threshold reduction is also linear.

The maximum threshold reduction, 14.45%, was obtained when the feedback is maximum, i.e., when the transmission in the VA is maximum—this occurs when 0V is applied to the VA. In contrast, the minimum amount of optical feedback occurs when 1V is applied to the VA, and produces a 0.62% threshold reduction—that reveals that the feedback is almost totally, but not completely suppressed. It is important to note that when we refer to the “solitary laser case”, the voltage applied to the VA was 5V, and the measured light transmission was 0%.

3. Speckle image acquisition and analysis

The image acquisition parameters in the CMOS camera were kept fixed: gamma = 0—dark image areas non-linear enhancement factor—, gain = 0, black level = 180 and pixel clock = 20 Hz. To reduce as much as possible the effect of noise, for each value of the pump current we adjusted the exposure time to avoid under-exposure, and we also made sure that we avoided over-exposure. We used exposure times such that 1) the distribution of pixel values covers a minimum of 75 bins and 2) the distribution of pixel values is included in all the range of values—i.e., the tail of the distribution is not “cut”. We verified that for exposure times that satisfy both criteria, the speckle contrast is almost insensitive to variations of the exposure time.

For each set of parameters—pump current and feedback strength—8 speckle images were recorded and for each image, the speckle contrast, SC, was calculated. The SC is the ratio between the standard deviation of the values of the pixels, and the average value, $SC = \sigma_I/\langle I\rangle$. The SC was calculated in the center of the image—in a centered circle of radius = 200 pixels—after subtracting the background—subtracting the value of the smallest pixel in the circle. In the results presented in the next section, the average of the 8 SC values is shown. The error bars that would represent the dispersion of the SC values are very small, even during the transitions, and therefore, not shown.

For each set of parameters, in addition of the 8 speckle images, the optical spectrum was acquired with the OSA, using the light that passed through the first MMF.

All the measurements were performed by increasing the injection current in steps of 1 mA and waiting, after each step, more than 30 seconds to let transients die way before recording the speckle images and the optical spectrum.

4. Results

Figure 3 displays the SC as a function of the injection current, and in color code—in logarithmic scale—the distribution pixel values. Panel (a) displays results for the solitary laser, (b) for the highest feedback level achieved when using the mirror and (c) for the highest feedback level achieved when using the grating. In the solitary laser case, the SC grows gradually with the injection current. In contrast, in both feedback configurations, the speckle contrast grows abruptly when the laser turns on—as it can be seen in Fig. 2, the threshold current for maximum feedback is about 36 mA. The distribution of pixel values reveals that an abrupt change occurs when crossing threshold.

An inspection of the optical spectra, shown in Fig. 4, allows to understand the different behavior of the speckle contrast, with and without feedback, seen in Fig. 3. For the solitary laser, Fig. 4(a), in the optical spectrum we see, when the laser turns on, two modes—a dominant mode and a side mode. With increasing current, the spectrum becomes monomode, up to about 60 mA, where we again see multimode emission with the coexistence of three modes. The optical spectrum is thus consistent with the smooth increase of the speckle contrast above the threshold, and with the small decrease of the SC that occurs at high currents. The observed red-shift of the emitted mode is a well-known consequence of thermal effects [3].

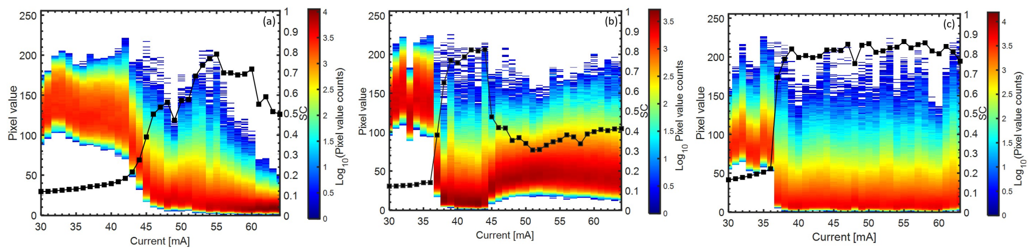

Fig. 3. Speckle contrast and distribution of pixel values—in log color code—for (a) the solitary laser, (b) the laser with the maximum feedback provided by the mirror and (c) the laser with maximum feedback provided by the grating. The black line marked with black squares indicates the speckle contrast value.

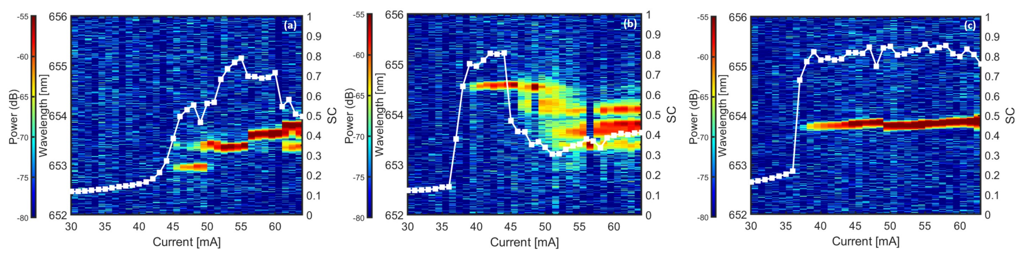

Fig. 4. Speckle contrast and optical spectrum—in color code—for the same conditions as in Fig. 3. The white line marked with white squares indicates the speckle contrast values.

When the laser receives maximum feedback from the mirror, Fig. 4(b), the optical spectrum shows monomode behavior in a narrow range of injection currents, as for currents above 45 mA there is an abrupt broadening of the optical spectrum that marks the onset of coherence collapse, i.e., chaotic emission.

On the other hand, when the laser receives maximum feedback from the grating, Fig. 4(c), only the abrupt transition to coherent emission is seen, since the second transition to coherence collapse is not observed—the optical spectrum remains monomode even at high injection currents. This is a consequence of re-injecting a single mode, in comparison with the feedback from the mirror, where all the modes are fed back to the laser.

Figure 5 shows, for the mirror configuration, the speckle contrast as a function of the two control parameters, the feedback strength and the injection current. In panel (a) we see that the transition gradually becomes abrupt with increasing feedback strength. In panel (b) the feedback strength is shown in the horizontal axis, quantified by the percentage of threshold reduction. The threshold current—marked with white symbols—linear decreases with increasing feedback. Below threshold, the laser emission is dominated by spontaneous emission, and the speckle contrast is quite low—dark blue region. For weak feedback—small threshold reduction— the speckle contrast increases smoothly with the pump current and reaches a high value for high currents—red region in the top-left corner. Thus, for weak feedback the behavior is similar as in the solitary laser.

On the other hand, if the feedback is strong enough —if it produces more than about 4% of threshold reduction— the speckle contrast increases abruptly and remains large for a range of pump currents values—red region above the white symbols.

However, for higher pump currents the speckle contrast abruptly decreases—light blue region over the red region—which marks the onset of coherence collapse. A similar diagram was obtained in [18], where the laser intensity was analyzed in the temporal domain. However, the

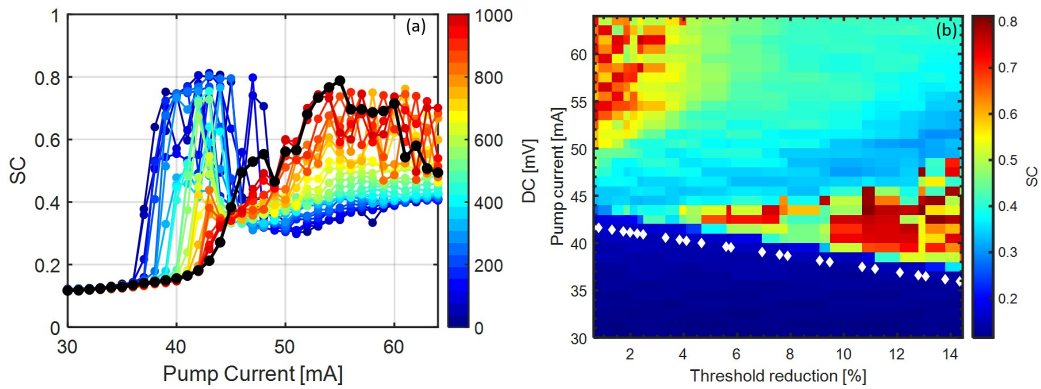

Fig. 5. (a) Speckle contrast as a function of the injected current for the different feedback strengths in the mirror configuration—black dots refer to the solitary laser. (b) Speckle contrast in color code as a function of the injected current and feedback strength, quantified by the threshold reduction, in the mirror configuration. The white symbols indicate the threshold current determined from the LI curve, Fig. 2 .

analysis in [18] was based on time series analysis of the output intensity, and thus, did not reveal the different level of coherence in the different regions.

4.1. Study of hysteresis phenomena

To check for hysteresis phenomena in the transitions from low-coherence to high-coherence radiation, and from high-coherence to coherence collapse we performed a second set of experiments with the mirror setup, where after reaching the maximum value of the injection current, we decreased the injection current back to the lowest value. The results are presented in Fig. 6, where we see that there is no hysteresis in the first transition—the turn on and turn off of the laser—while there seems to be some hysteresis in the second transition—to/from coherence collapse, revealed by a transition to/from low speckle contrast. Further studies are of course needed to analyze in detail the possibility of hysteresis when the injection current varies linearly in time—i.e., dynamical hysteresis. Such experiments were not performed due to the limitation of the lab equipment—the OSA and the CMOS camera are unable to measure fast changes in the optical spectrum and in the speckle pattern. We remark that in the experiments presented here the injection current was varied in steps of 1 mA, and to avoid transients we waited more than 30 seconds before recording the optical spectrum and the speckle images.

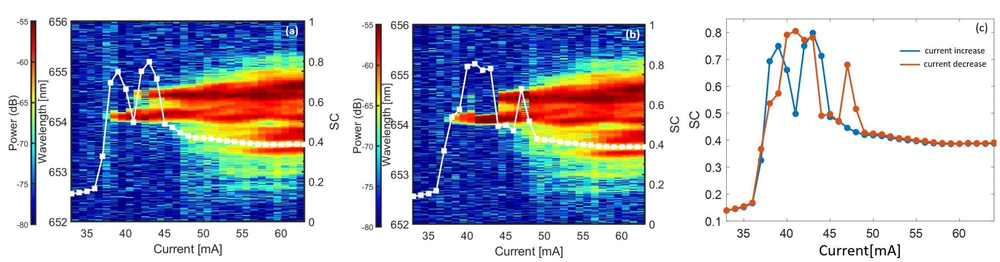

Fig. 6. Optical spectra and speckle contrast recorded when the injection current was increased (a), and when it was decreased (b). The white line marked with white squares indicates the speckle contrast values. Panel (c) shows the speckle contrast when the current increases (orange) and when it decreases (blue).

5. Conclusions

To summarize, we have studied experimentally the level of coherence of the laser light, when the injection current increases across the threshold and optical feedback is applied.

Through the analysis of speckle images—recorded with a CMOS camera, without the need of a high-resolution optical analyzer—we have found that strong enough feedback, from an external mirror or from a diffraction grating, induces an abrupt increase in the coherence of the laser light. The speckle contrast also reveals the transition to the chaotic coherence collapse regime, that occurs at high pump currents, when the light is fed back from a mirror; in contrast, with feedback from a grating the optical spectrum remains mono mode and the speckle contrast remains high.

We performed additional experiments to test for hysteresis in the transition from low to high-coherence emission, and found that the transition occurred at the same value of the injection current, when the current was either increased or decreased. Since all the experiments have been done by varying the current in small steps and disregarding transients, further research is needed to test for dynamical hysteresis when the current increases and decreases linearly.

While the transitions between regimes with different coherence levels—low-coherence, high-coherence and coherence collapse—are well understood in terms of feedback-induced regimes, the abrupt nature of the transition for strong enough feedback has so far been unnoticed—as is not revealed by the LI curves, shown in Fig. 2(a), nor by time-series analysis of the laser output intensity.

An important open question is which is the physics behind the abrupt increase of coherence during the off-on transition. We do not yet know and ongoing work is devoted to perform simulations using different types of single and multimode models [3,19,20].

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Data availability. The data is available from the corresponding author under reasonable request.

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