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Feedback induced polarisation switching in vertical cavity surface emitting lasers

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Abstract

We analyse the behaviour of a bistable vertical cavity semiconductor laser under the influence of optical feedback. Without feedback, this laser emits either vertically or horizontally polarised light with a region where polarisation bistability is observed. In this paper, we show that weak optical feedback can induce polarisation switching regardless of the polarisation of the re-injected light. These switches are quite similar to those observed in the current noise induced case. However, remarkable differences appear in the probability distribution of switching times depending on the polarisation state of the re-injected light. Experimental results detailing these differences are presented and the possible contributing mechanisms discussed.

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Keywords: Semiconductor; Lasers; Polarisation; Instability; Feedback

1. Introduction

The polarisation dynamics of axially symmetric vertical cavity surface emitting lasers (VCSEL) displays many interesting features [1]. In particular, these devices usually emit linearly polarised light along one of the crystal axis despite the presence of an axially symmetric optical cavity. This effect is generally attributed to the presence of non-isotropic strain fields which lift the degeneracy between the crystal directions and can result in a linearly polarised output [2]. In addition, studies have shown that polarisation switching between two orthogonal linear polarisations is commonly observed when one varies the injection current. This behaviour has generated many experimental and theoretical investigations and, even today, the origin of polarisation switching remains only partially understood.

When the current through such a device is varied, thermal effects can induce polarisation switching as described by Choquette and collaborators [2]. Such behaviour has been described using a two mode

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model, each mode having different gain properties [3]. However, further studies have shown that other mechanisms can also lead to polarisation switching. For example, San Miguel and collaborators have developed a rate equation model which describes polarisation switching, even if the two orthogonal modes experience the same gain [4]. Other analysis has shown that crystal strain can induce birefringence and control the polarisation behaviour [5]. Although, the origin of polarisation switching is not fully understood yet, polarisation switching can be used as a tool to examine the dynamics of bistable systems under the influence of noise. The addition of current noise has generated polarisation switching dynamics similar to the Kramer's escape problem of a particle in a double well potential [6]. With the addition of a small current modulation, one can study stochastic resonance [7,8]. Several authors have analysed the behaviour of VCSELs under the influence of optical feedback and have addressed the possibility of generating polarisation modulation [9,10] or have analysed the instabilities induced by optical feedback [11–14]. These latter studies have compared the behaviour of VCSELs with that of edge emitting lasers where low frequency fluctuations and coherence collapse are observed.

In this paper, we present experimental results detailing the appearance of polarisation switching in VCSELs due to weak delayed optical feedback. In the continuous wave (cw) regime, the device emitted horizontally or x-polarised light for low injection currents and vertically or y-polarised light for higher injection currents. For intermediary injection currents the two polarisations were stable, as shown on Fig. 1, and hysteresis was observed when the current was slowly varied. However the laser did not exhibit spontaneous polarisation switching except when noise was incorporated in the injection current as previously reported [6,7]. In this article, we study the influence of optical feedback in the region exhibiting bistability and notice that optical feedback also induces similar polarisation switching. This effect was observed for various experimental arrangements where a polariser or a quarter wave plate was incorporated in the external cavity. The appearance of polarisation switches for any angle of this optical component suggests that this phenomenon is associated with an enhancement of noise rather than an instability which should be model dependent.

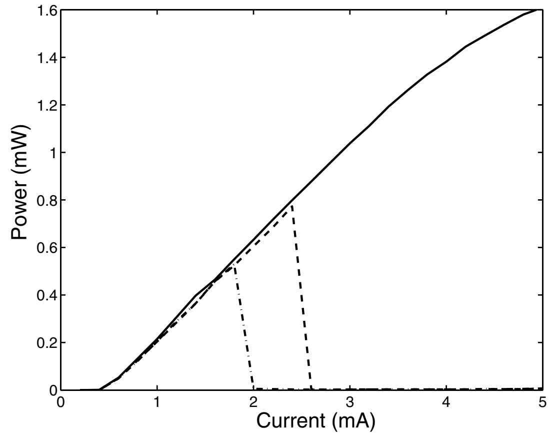

Fig. 1. Power–current characteristic of one of the linearly polarised modes as current is increased (dash–fash) and decreased (dash–dot) and the total power (solid). The laser operates on a single spatial mode in the range shown, note the presence of an abrupt switch-off just above 2 mA and the hysteresis in its position.

2. Experiment

The experimental setup was as shown on Fig. 2. The current to the VCSEL was stabilised to within

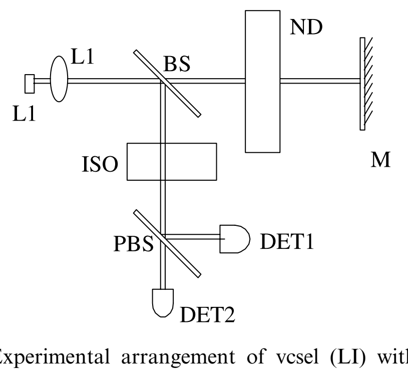

Fig. 2. Experimental arrangement of vcsel (LI) with optical feedback from mirror (M). The feedback level could be varied using a tunable neutral density filter (ND). Part of the laser output was extracted using a non-polarising beam splitter (BS) and, after optical isolation (ISO), was split into its constituent polarisations using the polarising beam splitter (PBS). A polariser could be placed after the neutral density filter (ND) to select a particular polarisation for feedback.

1 μA using the ILX LDX-3210 while its heat-sink temperature was controlled to within 10 mK using the Newport Model 350 thermoelectric cooler. The apparatus was mounted on a vibration stabilised optical table. Noise could be added to the DC current level from an Agilent 33120A function generator (8 MHz bandwidth) using a Mini-circuits bias tee (ZFBT-6GW). The external cavity length was fixed at $\simeq$1 m. Detection was isolated from the experiment (isolation of 40 dB) and consisted of two multi-mode fiber coupled Newport AD-300 detectors and limited in bandwidth by a 100 MHz oscilloscope. The VCSELs used were oxide confined type devices, lasing on a single mode at low currents. The devices, which lased at 850 nm could exhibit a number of polarisation switching points as shown on Fig. 1 where there is initially a switch at around 2 mA and further mixing around 6 mA (not shown on figure). As the switching observed at high injection current involved higher order transverse modes, we concentrated on the region around 2 mA where single mode operation is observed. Without feedback and/or current noise, the laser emitted in one fixed polarisation. Throughout the paper, we will denote by i_A and i_B the low and high current boundaries of the hysteresis region (1.995 and 2.405 mA, respectively). Thus for $i < i_A$, the laser emits only x-polarised light, both polarisation can be observed for $i_A < i < i_B$ and only y-polarised light is observed for $i_B < i$. It is worthwhile to note that we do not observe spontaneous polarisation switching even near i_A or i_B.

3. Effect of isotropic feedback

The range of currents exhibiting bistability decreases when the device is submitted to weak isotropic feedback, i.e. i_A increases with feedback and i_B decreases. For extremely low feedback level, corresponding to a threshold reduction of about 3%, spontaneous polarisation switching occurs for injection currents larger/smaller but close to i_A/i_B (see Fig. 3(left)). As for noise induced polarisation switching, the total power remains constant throughout delay induced switches. For simplicity, we will describe the effect of optical feedback near the upper polarisation switching point i_B. In the following, we study the polarisation dynamics starting from the x-polarised state. For $i > i_B$, we observe a single switch as the laser relaxes to the y-polarised state. For a small range of currents lower than i_B (width 10 μA), a dynamical transient occurs, where the laser switches several times between the x and y-polarised states before relaxing to the y-polarised state. For a lower range of injection currents (width 10 μA) the stable, y-polarised state is never reached and continuous spontaneous switching of the laser's polarisation is observed. The mean residence time in the y-polarised state is on the order of a few μs while the mean residence time in the x-polarised state is a few milliseconds. Similar behaviour was observed near the lower current limit i_A, but with reversed polarisation. At higher feedback levels, corresponding to threshold reductions >5%, more complicated fluctuations with characteristic time-

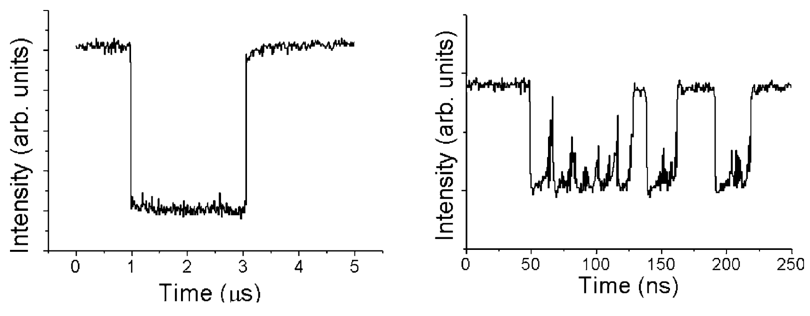

Fig. 3. Example of feedback induced polarisation switch (left) and appearance of round trip instabilities as feedback is increased (right). In both cases the total power is constant.

scales longer than the external cavity roundtrip time appeared (see Fig. 3(right)). These were present in both polarisations and anti-correlated as the total power remained constant. Similar behaviour to these more complicated fluctuations has recently been reported in [15].

4. Statistical behaviour

To further analyse the properties of the polarisation dynamics, we measured the residence time distribution (RTD) of the two polarisation states. Each RTD was constructed from over 2000 switching events. For the range of feedback values used, and operating close to i_B, the probability distribution for the x-polarisation followed an exponential law similar to the noise induced case (see Fig. 4). This indicated that the switching rate remains constant over the experimentally measured residence times as in Kramer's theory. This contrasted with the RTD for the y-polarisation state whose shape varied as the feedback level was varied as shown on Fig. 5. For feedback levels corresponding to threshold reductions <3% (see Fig. 5(i)), the RTD had an exponential decay whose slope changes abruptly near 3 μs. This indicates that Kramers theory could apply for both slow and fast switching times, but the height of the potential barrier and/or the noise level abruptly changes if the particle remains in one well for a time longer than some critical time. Such a scenario occurs in time delayed systems as described in [16,17]. In our case, it is worthwhile noticing that the change in barrier height occurs after a few microseconds, which is the typical timescale for thermal processes in semiconductor lasers.

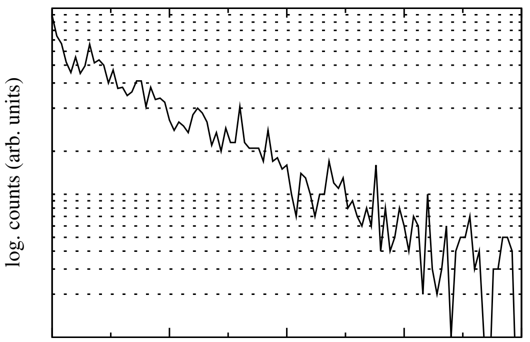

Fig. 4. Probability distribution for the more stable x-polarisation at the weakest feedback level, biased just below i_B. Please note that the mean residence time for the more stable state is of the order of 50 ms while the mean residence time for the less stable state is of the order of 5 μs.

As we increase the feedback level (threshold reductions between 3% and 5%) the current range over which switching occurs increases (see Fig. 5(ii),(iii)). However, the RTDs in these cases displayed the appearance of 'resonances' whose values varied with injection current and feedback level. The time scale for these phenomena is on the order of magnitude of the thermal processes commonly observed in VCSELs [18]. These resonances disappear when the feedback is further increased (threshold reductions >5%) and the probability distribution of residence times recovers the shape observed at the lowest feedback level (see Fig. 5(iv),(v)).

5. Effect of polarised feedback

The behaviour described above was compared to the case were feedback was provided to a single polarisation only. This was achieved by introducing a polariser into the external cavity. Dynamical polarisation switching was observed for any angle of the polariser. Some RTDs are shown on Fig. 6 for the case where the polariser chooses the x-polarisation state for re-injection. The histogram shape has changed dramatically compared to the unpolarised feedback case. In this case, we observe RTD shapes which are much closer to exponential decay behaviour without any resonances. In addition, for a fixed feedback level, the average residence time of the y-polarisation increased as the current increases until the y-polarisation state become stable. Indeed, this exponential behaviour persists to higher feedback levels (see Fig. 6(iv)). In this case, the amplitude fluctuations, observed in either polarisation, depends on the polarisation of the emitted light. When the laser's polarisation is orthogonal to the axis of the polariser, the amplitude of the fluctuations are similar to those observed in the cw regime when noise is added.

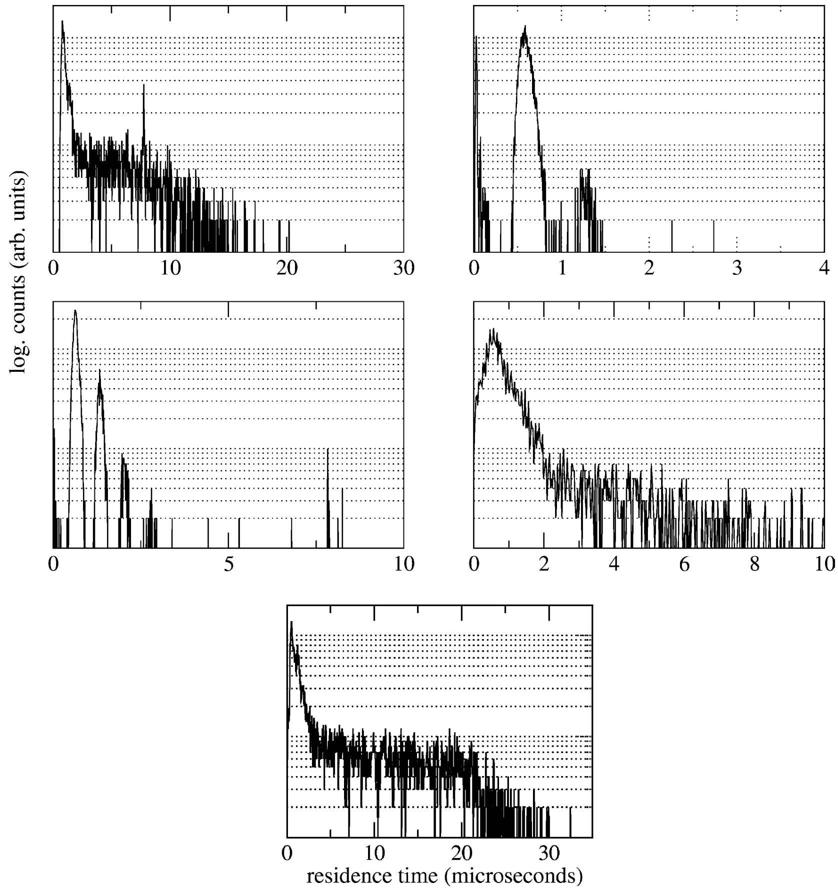

Fig. 5. RTD for the y-polarisation around i_B. (i) (Top-left) At lowest feedback level (threshold reduction <3%) biased just below i_B. Next, at increased feedback level (threshold reduction between 3% and 5%) for different currents: (ii) (Top-right) 2.263 mA and (iii) (middle-left) 2.282 mA. Finally, maximum feedback level (threshold reduction >5%) for different currents: (iv) (Middle-right) 2.104 mA and (v) (Bottom) 2.135 mA.

This contrasts with the situation where the polarisation of the emitted light is parallel to the axis of the polariser. In this case, we notice a higher level of fluctuations, as shown on Fig. 7. However, these fluctuations are anti-correlated and the noise level in the total intensity is low. Thus, the probability distributions of residence times are similar to that observed when noise is added to the bias and no resonances are observed.

6. Discussion

The experimental results presented above demonstrate that optical feedback induces polarisation switching in VCSEL's. The average residence time in each state is, however, shorter than that observed with current induced noise. These switches also differ from polarisation switching observed without feedback as they only occur at the boundary of the hysteresis curve. It is worthwhile pointing out that the main difference between optical feedback and current noise induced polarisation switching is the role of the phase of the optical field. The optical phase does not play any role when the free running laser is submitted to noise but may play an important role in inducing polarisation switching when the VCSEL is submitted to optical feedback. The introduction of weak optical feedback from a long cavity as pre-

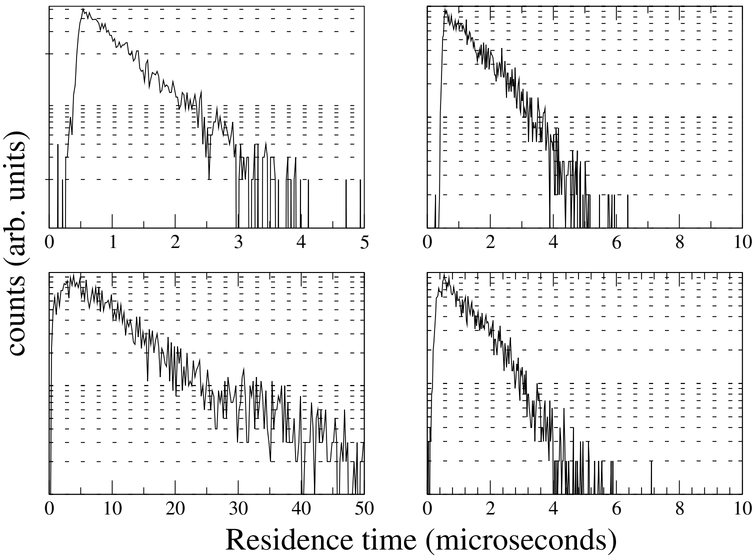

Fig. 6. RTD for the y-polarisation with polarised feedback into the x-polarisation state: at lowest (polarised) feedback level for different currents (i) 2.360 mA (ii) 2.372 mA (iii) 2.391 mA: at higher (polarised) feedback level at a current level of 2.376 mA.

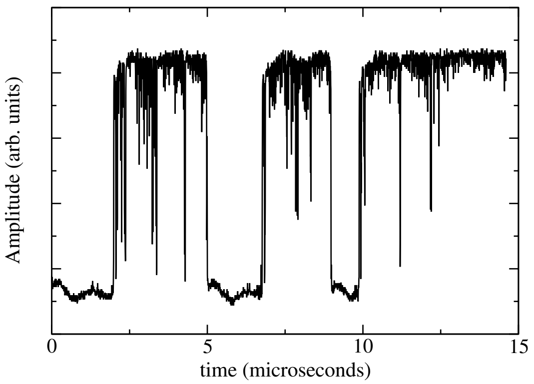

Fig. 7. Polarised output of the laser where the polarised feedback is in the same plane as measured. Note the high level of amplitude noise in the polarisation measured. This noise is absent from the total power and constitutes anti-phase dynamics.

sented in this paper is not sufficient to build coherent effects and, as a result, one could consider that the phase difference between the laser and the re-injected light is a random variable. In this picture, optical feedback is similar to an extra source of noise and this could explain the origin of the polarisation switches described above. The timescale of the resonances observed in the RTDs suggests a role for thermal processes, however the origin for the shift in frequencies over such a small feedback range is not apparent. As these were not observed when the laser was submitted to current noise, this suggests that thermal effects might induce changes of the refractive index and external cavity coupling and thus induce these resonances. However, further experimental work is required to investigate these points.

7. Conclusions

In conclusion, we have shown experimentally that weak optical feedback induces polarisation switching in VCSELs where the polarisation state of the laser switches to an orthogonal state for a time much longer than the feedback time. This switching appears regardless of the polarisation properties of the re-injected light. The RTDs for each of the polarisation states indicates that this process is similar to previously studied, noise driven polarisation switching. However, the presence of feedback modifies the shape of the probability distributions and, for some values, induces resonances.

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