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Mapping transients in the nonlinear dynamics of an optically injected VCSEL

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ABSTRACT

Optical injection is one of the key methods for invoking nonlinear dynamical outputs in laser systems. The system parameters that are used to control the nature of the output from such a system are the injection strength and the frequency detuning between the optical frequency of the free running master and slave lasers. A map of the dynamics can be generated using a number of measurands to facilitate identifying the fundamentally different dynamical regions in the injection-strength/frequency-detuning parameter space. Herein we describe a set of automated algorithms used to establish several measures to identify transients and instabilities in the nonlinear dynamical output of an optically injected vertical cavity surface emitting laser (VCSEL), for set and unchanging driving parameters.

Keywords: Nonlinear dynamics, VCSEL, optical injection, transient dynamics, orthogonal injection

1. INTRODUCTION

Optical injection, the process of injecting the light from a master laser into a second slave laser, is known to cause a range of dynamical states, including periodicity and chaos, in the output power of the slave laser of the system1, 2. The dynamic state can be controlled by varying the level of optical power injected into the slave laser and/or the frequency detuning between the free running optical frequencies of the master and slave lasers. Optically injected laser systems based on solid state lasers3, 4, edge emitting semiconductor lasers5, and vertical cavity surface emitting lasers (VCSELs)6-10 have been characterized previously. A 2-D dynamical map for a given system can be produced by categorizing the dynamical output state as a function of the injection strength and frequency detuning. A number of measurands have been developed and used to identify the regions occupied by different dynamical states within the parameter space11, 12. This work refers to an optically injected 1550 nm VCSEL system8. The isotropic nature of the active region in VCSELs results in unstable polarization of the output. Switching between two orthogonally polarized modes (associated with the fundamental spatial mode) is an additional layer of complexity in the dynamics seen in these devices13, 14. In this work the optically injected signal is polarized orthogonally to the main free-running VCSEL polarization mode.

Traditionally, these types of systems were characterized by manually observing electrical and optical spectral information. More recently, fast optical detectors and a high bandwidth real-time oscilloscope allow the recording of temporal output power dynamics, resolved into the two orthogonally polarized components. When experiment design incorporates computer control and data logging, high density data sets can be generated which can be used to produce high resolution maps of the dynamical states achievable with the system. Previous analysis of this system, in which light from a master laser has been injected into the orthogonally polarized mode of the slave VCSEL, has identified several regions of different dynamics, including stable injection locking, limit cycle oscillations, period doubled dynamics, and nonlinear dynamics15. Here-in we take this type of analysis a step further. The output power time series are analysed to reveal regions of the dynamical map where the nonlinear dynamical state changes over time. An appropriate time window or windows for such an analysis needs to be chosen following an initial appraisal of representative time series. Algorithms have been developed to compute measures from the experimental time series which identify points in the map where the dynamical output state has instability in time. The quantitative value of the measurand, which reveals variation in time of the dynamic states, is mapped to generate a map which gives additional insight into the system...
output. This is especially valuable when the system is to be employed in applications, for which regions where the dynamics change in time generally need to be avoided.

2. EXPERIMENT

The experimental setup is described in detail elsewhere. The key features are reproduced in Fig. 1.

![Experimental Setup Diagram]

Figure 1. Setup used to record polarization resolved output power time series from the VCSEL subject to orthogonally polarized optical injection.

The slave laser used in the optical injection experiment was an InAlGaAs/InP quantum well 1550 nm VCSEL. The injected light was supplied by a tunable external cavity master laser and a polarization controller was used to orient the polarization direction so that it was orthogonal to the free-running VCSEL lasing mode. Threshold current of the VCSEL was 1.8 mA at 293 K. During the experiment the VCSEL injection current was 9 mA (5 times above threshold) and the relaxation oscillation frequency was approximately 4 GHz at this bias. For all conditions in this experiment the device operated on a single transverse mode. The two modes seen in the inset optical spectrum of Fig. 1 are the orthogonally polarized modes of the VCSEL. The main lasing mode (-5 dBm) and subsidiary mode (-44 dBm) are separated by approximately 60 GHz (0.5 nm). These modes will be referred to as the 'parallel' (main) and 'orthogonal' (subsidiary) polarization throughout this paper.

A variable optical attenuator (VOA) was used to control the injection strength monitored by sending 15% of the signal to a power meter. The remaining 85% was injected, with unspecified coupling efficiency, into the slave VCSEL. The output of the VCSEL was sent via an optical circulator to the detection arm of the experiment. Prior to detection, the emission was amplified by passing through an erbium-doped fibre amplifier and the amplified spontaneous emission noise was removed with an appropriate bandpass filter. The resulting signal was split into parallel and orthogonal polarization components using a polarization beam splitter. Two closely matched photodiodes (12 GHz bandwidth) were used to simultaneously monitor each of the polarizations on a 13 GHz real-time oscilloscope (Agilent DSA91304A). Output power time series of 100 ns (32 017 data points) in length were recorded.

The purpose of the experiment was to examine the temporal behaviour of the system for a range of injection strengths and optical frequency detuning in order to assess the nature of the observed dynamic states. Injection strength ($K$) is defined as the power in the injection signal normalized to the power of the free running VCSEL. Optical frequency detuning ($\Delta f$) is the difference between the centre optical frequency of the injected mode and the centre frequency of the orthogonally polarized mode of the slave VCSEL.

The data collection procedure involved stepping the optical frequency detuning through 40 levels from -10.9 GHz to +13.1 GHz. At each detuning, the injection strength was stepped through 47 values between -15 dB up to +7.2 dB. The output power time series was recorded simultaneously for both parallel and orthogonal polarizations at each of the 2021 different parameter combinations of injection strength ($K$) and frequency detuning ($\Delta f$).
3. RESULTS AND DISCUSSION

Previous analysis of this system resulted in a manually generated map showing the boundaries between distinct dynamic regions of stable injection locking (IL), limit cycle or period-1 (P1), period doubling (P2) and chaos (C)\textsuperscript{15}. The map, which is reproduced here in Fig. 2, also indicates the polarization switching region (PS).

![Map of dynamic regions](image)

**Figure 2.** Manually generated map of the dynamic regions of a 1550 nm VCSEL subject to orthogonally polarized optical injection as a function of optical frequency detuning between master laser and slave VCSEL and the optical injection strength. Reproduced from the work of Schires \textit{et al.}\textsuperscript{15}.

In some regions of the parameter space the general nature of the dynamics was observed to change dramatically even though the device was held under constant driving conditions. From an applications perspective, if this system were to be used as a source of either periodic signals or chaotic signals, then this dynamic switching is undesirable. Most applications would require continuous generation of a specific dynamic once set in a particular mode of operation.

In this work automated algorithms were developed to analyse the time series data to look for evidence of this transient behaviour for fixed parameter settings. One of the measures used to identify dynamic instabilities is variation in period between local maxima in the slave VCSEL output power time series\textsuperscript{16}. The map in Fig. 3 displays this information as the standard deviation in time interval between local maxima as a percentage of the mean period between peaks for the whole time trace. The grey shaded area in the map is where the slave laser is injection locked and essentially CW with no interesting dynamics (high mean power, low peak-to-peak amplitude).

The regions of the map that show a low percentage of standard deviation correspond to very regular periodic oscillations of the output power (Fig. 3(a)). Those regions with larger values are identified as those with irregular nonlinear dynamics (Fig. 3(b) and (c)). Knowledge of the boundaries and stability of the different regions is important so that certain ranges of injection and/or detuning can be targeted or avoided, depending on the application. For most applications it is required that the dynamic state be stable. Closer inspection of the “unstable” regions identified in Fig. 3, where the dynamic output is changing in time, over the measurement window of 100 ns, reveals clear differences between positive and negative frequency detuning. The small region of unstable dynamics along the boundary of the injection locked region for negative frequency detuning is generally populated by spiky dynamics, such as those seen in Fig. 3(b). The dynamics here can be quite intermittent and nonstationary, even though the parameters are fixed. In contrast, the dynamics seen for positive frequency detuning tend to be more like those shown in Fig. 3(c). This type of output appears to be a more stable nonlinear dynamic, typical of that seen in other chaotic semiconductor laser systems\textsuperscript{17}, such as low frequency fluctuations. In this region, the ‘period’ of the dynamics is typically much less stable than other regions in the map.
Another technique used to identify unstable dynamics makes use of variation in the peak-to-peak amplitude of the output power time series\textsuperscript{16}. A sliding window of approximately 625 ps (200pts) in length is passed over the full 100 ns (32017pts) normalized time series. At each of the 160 windows the peak-to-peak amplitude within is recorded and the standard deviation is mapped to identify unstable dynamics.

Combining these maps and using the information regarding the temporal and amplitude stability assists in the generation of a detailed overall picture of the dynamics produced by this system. The automated processes can make use of large data sets to identify transient regions that would otherwise be intractable to do manually. Contrasting these automated maps (Figs. 3 and 4) with manually generated maps (Fig. 2) highlights a previously unidentified region of instability for positive detuning along the P1 boundary for low injection strengths. The automated maps also highlight parts of the...
negative detuning parameter space that were identified as chaotic in Fig. 2, actually display a transient switching behaviour, typical of that seen in Fig. 3(b). This ‘unstable instability’ is a previously unknown feature of these laser systems that has been identified by the techniques developed here.

The additional information that high resolution experimental maps provide is also valuable for comparison with the prediction of theoretical models. The transient behaviour in some regions of the parameter space, such as that seen in Fig. 3(b), is not predicted by current models of the system. It is possible that this type of dynamic is analogous to excitability that has been predicted and observed in edge-emitting laser systems\textsuperscript{18, 19}, this should be followed up in the future in a detailed study of the theoretical model of a VCSEL under orthogonally polarized optical injection.

4. CONCLUSION

Maps have been generated which highlight instabilities in the nonlinear dynamics of an optically injected vertical cavity surface emitting laser system subject to varying injection strength and frequency detuning between the master and slave lasers. These maps build on previous analyses that identify the different basic regions of operation. The current maps display measurands, calculated using automated algorithms, which can identify instabilities in the experimental output power time series for set operating parameters. Systematic evolution of these variations is found in some regions of the map for an optically injected VCSEL system. Identification of these regions is important so that parameters can be selected to either target or avoid certain regions, depending on the dynamical state required, and the specification on stability of this state over time that is needed, for an application.

This type of analysis will prove valuable in testing theoretical models of nonlinear laser systems when the simulated output is being compared to experimental output. Analysing simulated data time series for sensitivity to variation in time becomes an additional tool for identifying if all the physics of the system is incorporated into the model being used. Knowledge of the different types of dynamics a system is capable of producing, as well as the regions of parameter space which are susceptible to instabilities, can inform whether a model is accurately describing the system.

REFERENCES