

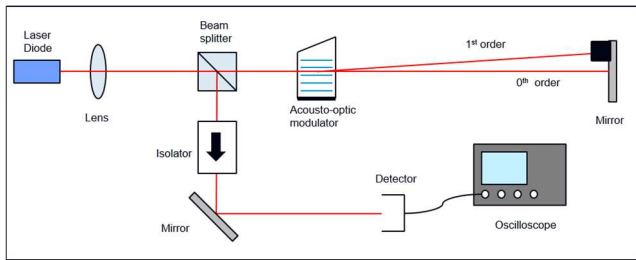
# A New Approach to Modelling the Coherence of Optical Feedback in Dynamical Semiconductor Laser Systems

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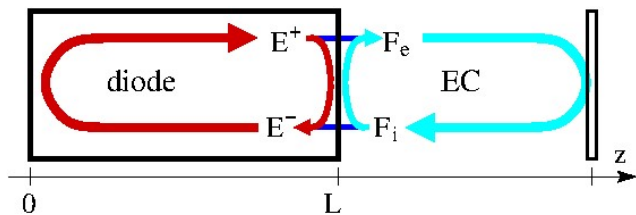
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It is well known that optical feedback in a laser system, such as the semiconductor laser-based one shown schematically in fig.1, can either stabilise or destabilise its output power and spectral characteristics. Semiconductor lasers have a level of sensitivity to optical feedback that is far greater than most lasers [1-3]. The current interest in using semiconductor laser with optical feedback systems, including versions implemented as integrated devices, in, for example, random number generation, reservoir computing and secure communications [1-3], sustains vigorous research activity in the field. The high, and increasing, potential for making strong connections between the predictions of increasingly sophisticated theoretical models of these complex systems and experimental measurements also reinforces the sustained activity in the field.

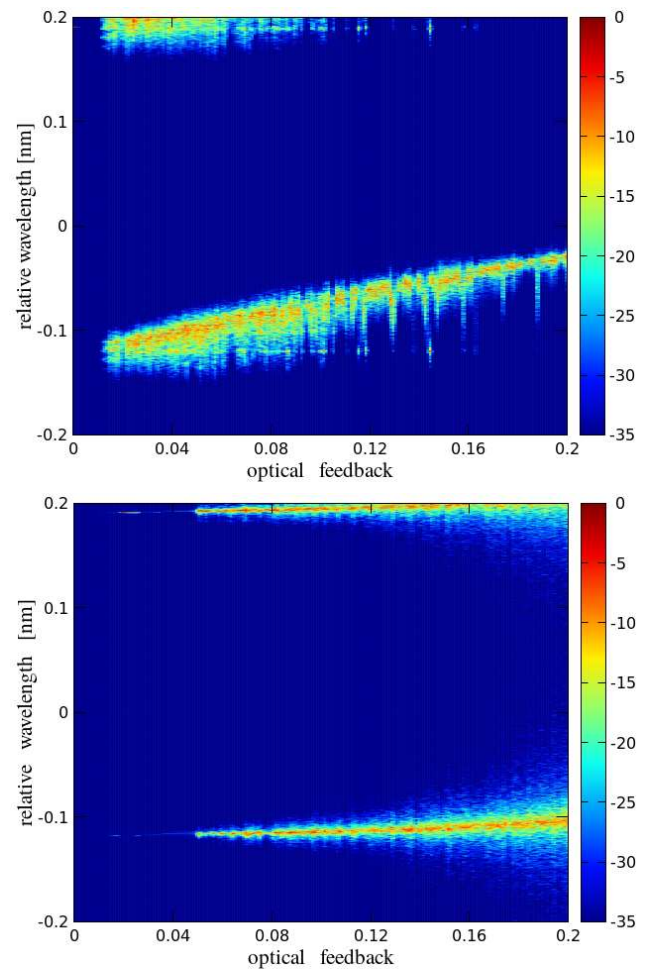


**Figure 1: Schematic of an experiment setup for studying a semiconductor laser with delayed optical feedback from an external mirror system (modified from [4]).**



**Figure 2: Schematic of a diode laser with an external cavity which informs the travelling wave model used.**

The aspect of the optical feedback in the semiconductor laser system that is investigated here is its coherence. There is some ambiguity in the literature about what is meant by coherent versus incoherent feedback. Historically, there has been an understanding, not always made explicit, that shorter external cavities will have coherent feedback. The large linewidths of order 100-200 MHz for free running Fabry-Perot-cavity-based semiconductor lasers were surprisingly large when first observed [5]. Such linewidths mean an external cavity with round trip length of order 1-2 metres would have an optical feedback field that was at best



**Figure 3: The optical spectrum as a function of optical feedback level. Colour scale is proportional to amplitude on a logarithmic scale. The spectral width of the individual modes broadens with feedback. Two (of many) adjacent longitudinal modes of the laser spaced by 0.3 nm are shown. The optical feedback fraction is increased from 0 to 0.2. Top:  $D=10^8 \text{ s}^{-1}$ . Bottom  $D=10^9 \text{ s}^{-1}$ .**

partially coherent on temporal coherence grounds. Long external cavity systems have been reported as having incoherent feedback on this basis. It is also the case that the optical feedback field is not an ideal plane wave after it has been propagated through the collimating and refocussing lens shown in Fig. 1. Differences in the wavefront shape of the feedback field as compared to the emitted field have been visualised through interference fringes and changes in beam shape due to destructive interference [6, 7]. Such variations in spatial coherence can be thought of as effective phase shifts in the one-dimensional propagation model.

A systematic approach to achieving incoherent feedback in experimentally studied semiconductor laser systems has

been to rotate the polarisation of the feedback field by 90 degrees so that the emitted TE mode is feedback into the TM mode. There are many cases of this approach in the literature, especially applied to vertical cavity surface emitting lasers (VCSELs) where polarisation dynamics are prevalent. Application to Fabry Perot semiconductor lasers has shown that delayed incoherent feedback leads to differentiable non-linear dynamics as compared to coherent feedback, with a major feature being the suppression of the reduced threshold current as the optical feedback fraction increases at a given injection current [8-10]. Theory for the system has been implemented with a modified Lang-Kobayashi model valid for weak feedback levels [9], and a modified travelling wave model [10]. The incoherent nature of the optical feedback is treated by including it in the dynamics for the carrier density only, and omitting it from the coupled photon density rate equation (L-K model, [9]) or the slowly varying complex field travelling wave equations [10]. In [9] experiments were completed which aimed to investigate a mixture of coherent and incoherent delayed optical feedback by using a quarter wave plate to rotate the polarisation of the optical feedback field by 45 degrees using a quarter wave plate. From these results the authors concluded that dynamics with a mixture of coherent and incoherent feedback is most likely the dynamics that are reported from experimental systems. This raises the prospect that it is a differing effective coherence (partial coherence) of the delayed optical feedback in different experimental studies that may explain a significant part of the differences in the details of the dynamics that have been observed. In order to test this theoretically a model that allows the effective coherence of the optical feedback to be systematically varied is required and this is what is reported here-in.

## 1. Travelling Wave Model

For simulations of the spatio-temporal dynamics in the Fabry-Perot type diode laser we apply the traveling wave (TW) model, which is a 1(space)+1(time) dimensional system of partial differential equations describing the longitudinal and temporal evolution of counter-propagating optical fields,  $E^+(z, t)$  and  $E^-(z, t)$ , and the carrier density  $N(z, t)$ :

$$\frac{n_g}{c_0} \partial_t E^\pm \pm \partial_z E^\pm = (-i\beta(N, |E|^2) - \Delta) E^\pm + F_{sp}^\pm,$$

$$\beta = \left[ \delta_0 - i \frac{\alpha_0}{2} \right] + \left[ \alpha_H + \frac{i}{1 + \varepsilon |E|^2} \right] \frac{g(N)}{2},$$

$$\partial_t N = \frac{I}{qV} - R(N) - \frac{c_0}{n_g} \Re \left( \bar{E}, \left( \frac{g(N)}{1 + \varepsilon |E|^2} - 2\Delta \right) E \right).$$

Here,  $g(N)$  and  $R(N)$  are the linear gain and cubic recombination functions,  $\Delta$  is the linear operator describing the (wavelength dependent) material gain dispersion,  $\bar{E}$  denotes the complex conjugate,  $|E|^2 = |E^+|^2 + |E^-|^2$  is the local photon density, whereas  $F_{sp}^\pm$  are the Langevin noise source contributions to the optical fields. For a detailed description of these functions and the remaining model parameters, see Refs. [11, 12]. At the facets of the diode,  $z=0$  and  $z=L$ , the optical field satisfy the reflecting boundary conditions

$$E^+(0, t) = -\bar{r}_0 E^-(0, t), E^-(L, t) = r_L E^+(L, t).$$

In the presence of the optical feedback from the conventional external cavity, see Fig. 2, the second of these conditions is replaced by the relations

$$E^-(L, t) = r_L E^+(L, t) + (1 - |r_L|^2)^{1/2} E_i(t),$$

$$E_e = -\bar{r}_L E_i(L, t) + (1 - |r_L|^2)^{1/2} E^+(L, t),$$

with the reinjected and emitted fields  $E_i$  and  $E_e$  related by  $E_i(t) = \eta e^{i\phi} E_e(t - \tau)$ , where  $\eta$  represents the part of emitted field intensity which returns to the laser diode, and  $\tau$  is the external cavity roundtrip time.

The TW model allows moderate and strong optical feedback regimes to be considered and has been applied successfully to external cavity diode lasers where the optical length of the external cavity is comparable to the diode length [13] and also to semiconductor ring lasers [14]. Here-in it is applied to a Fabry Perot edge emitting semiconductor laser with one facet coated for high reflectance,  $r_0 = \sqrt{0.95}$ , and the facet facing the external cavity coated for low reflectance,  $r_L = \sqrt{0.05}$ . The parameters used in the model have been translated from those used in [15] intended to model an APL-830-40 laser as used in the experimental studies described in [4] and many other published studies.

The coherence of the delayed optical feedback field is reduced systematically by introducing several levels of phase noise to the reinjected field at the laser facet facing the external cavity (see Fig. 2) as per the expression below:

$$E_i(t) = e^{i\zeta(t)} [\eta e^{i\phi} E_e(t - \tau)].$$

$\phi$  is the fixed phase change of the complex field amplitude during the field propagation in the external cavity. The Gaussian random process  $\zeta(t)$ , with zero mean, represents the phase noise. Here we assume, that during propagation within the external cavity the field is losing its coherence with the rate  $D = 10^r \text{ s}^{-1}$  which defines the variance of the process. In the simulations the range  $r = 1-12$  has been investigated. With a value for  $\tau$  of 4.5 ns, the rate of  $10^9 \text{ s}^{-1}$  guarantees that the phase of the reinjected field is arbitrary.

## 2. Results and Discussion

The simulated quantities allow the time series, the optical spectra of the longitudinal modes, and the power spectrum to be viewed at different resolutions to show the detail of the dynamics. The time series can in turn be analysed to identify dynamical outputs such as low frequency fluctuations, regular pulse packages, chaos and its complexity. Figure 3 demonstrates the key initial finding of this research. The detailed dynamics of the time varying output power of the system (not presented) do show demonstrable systematic evolution with increasingly incoherent optical feedback. But the main transition to what is consistent with incoherent feedback as achieved by using rotation of the polarisation of the optical feedback field by 90 degrees in previous work [8-10], is shown in Fig. 3, bottom. In the top image, for a rate of  $10^8 \text{ s}^{-1}$ , the central wavelength of the longitudinal mode increases with optical feedback, as is expected for coherent feedback. The spectral width also broadens with a sequence of varying bandwidth as a function of optical feedback strength increases shown in fig. 3 (top). The optical bandwidth of a single longitudinal mode tends to, at best, cover the wavelength range between the feedback-governed higher wavelength and the free-running lower wavelength. There is an increasing trend to a narrower optical bandwidth about the optical feedback

governed wavelength as the optical feedback factor,  $\eta$ , increases. This is particularly prevalent for  $\eta$  greater than 0.16 in fig. 3 (top). An increase in rate D by a factor of ten sees the wavelength remain at its free running value, with just a small increase for the higher feedback values. Note that an optical feedback factor of  $\sim 0.2$  is about the highest achievable in experimental systems using conventional feedback when mode matching, coupling efficiency and other technical limitations are taken into account. This unchanging central wavelength is consistent with the observation of no reduction in laser threshold current that has been reported for incoherent optical feedback [8-10]. As previously noted  $10^9 \text{ s}^{-1}$  is the rate that achieves random phase for the reinjected field. Once this transition has occurred the signature of the optical spectrum of a given longitudinal mode remains as shown in Fig. 3 (bottom) up to rates of  $10^{12} \text{ s}^{-1}$ .

The form of the broadening of the optical spectrum of a given longitudinal mode is informative. For partially coherent feedback, as per Fig. 3 (top), most of the broadening is on the low wavelength side of the centre wavelength of the mode. The bandwidth of chaotic output is primarily spreading towards the free running wavelength. This is also observed for all rates below  $10^8 \text{ s}^{-1}$ . In contrast, the bandwidth associated with increasing incoherent feedback spreads symmetrically about the centre wavelength. This prediction of the theoretical modelling can now be applied to the results of experimental studies and may ultimately become a method for indirectly determining the coherence state of the optical feedback.

In conclusion a new method for theoretically modelling the effective coherence of an optical feedback field has been developed and incorporated into a sophisticated travelling wave model of delayed optical feedback in semiconductor lasers. The method allows the coherence of the optical feedback field to be explored from fully coherent to fully incoherent. The model has already given new insights into the impact of coherence in this context. It remains to be confirmed, but the study to date suggests that much or some of the differences observed in detailed dynamics in experimental systems in different laboratories may be due to differences in the effective coherence of the optical feedback.

### 3. Acknowledgement

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### 4. References

- [1] Eds. D. M. Kane and K. A. Shore, *Unlocking Dynamical Diversity: Optical Feedback Effects on Semiconductor Lasers*, Wiley & Sons, 2005.
- [2] Miguel C. Soriano, Jordi Garcí'a-Ojalvo, Claudio R. Mirasso and Ingo Fischer, "Complex photonics: Dynamics and applications of delay-coupled semiconductor lasers", *Reviews Of Modern Physics*, Volume 85, 422-470 (2013).
- [3] M. Sciamanna and K. A. Shore, "Physics and applications of laser diode chaos", *Nat. Photonics* 9, 151 (2015).
- [4] J. P. Toomey and D. M. Kane, "Mapping the dynamic complexity of a SLwOF using PE," *Optics Express* 22(2), 1713-25, (2014).
- [5] Mark W. Fleming and Aram Mooradian, "Fundamental line broadening of single-mode (GaAl)As diode lasers", *Appl. Phys. Lett.* 38, 511 (1981).

- [6] D M Kane and A P Willis, "External cavity diode lasers using different devices and collimating optics", *Appl. Opt.* 34, 4316-4325, (1995).
- [7] D M Kane and V G Ta'eed, "Spatial Beam Profiles from a System of Laser Diode with Optical Feedback – the Importance of Interference", *Appl. Opt.*, 24, 4316-4321, (2001).
- [8] J. Houlihan, G. Huyet and J. G. McInerney, "Dynamics of semiconductor laser with incoherent feedback", *Opt. Commun.* 199, 175 (2001).
- [9] R. Ju, Y. Hong, P. S. Spencer, "Semiconductor lasers subject to polarization-rotated optical feedback", *Proc. SPIE* 6115, 61150K (2006).
- [10] C. Masoller, C. Serrat and R. Vilaseca, "Modelling multi-longitudinal-mode semiconductor lasers with incoherent feedback", *Phys. Rev. A* 76, 043814, (2007).
- [11] M. Radziunas, "Traveling wave modeling of nonlinear dynamics in multisection semiconductor laser diodes", Chapter 31 in J. Piprek (Ed.), *Handbook of Optoelectronic Device Modeling and Simulation: Lasers, Modulators, Photodetectors, Solar Cells, and Numerical Methods*, Vol. 2, pp. 153-182, CRC Press (2017).
- [12] U. Bandelow, M. Radziunas, J. Sieber, M. Wolfrum, "Impact of gain dispersion on the spatio-temporal dynamics of multisection lasers", *IEEE J. of Quantum Electronics* 37(2), 183-188 (2001).
- [13] M. Radziunas, V. Z. Tronciu, C. Kürbis, H. Wenzel, A. Wicht, "Study of microintegrated external-cavity diode lasers: simulations, analysis, and experiments". *IEEE J. Quantum Electron.* 51, 2000408 (2015).
- [14] M. Radziunas, M. Khoder, V. Tronciu, J. Danckaert, and G. Verschaffelt, "Semiconductor ring laser with filtered optical feedback: traveling wave description and experimental validation", *J. Opt. Soc. Am. B*, 359(2), 380-390 (2018).
- [15] Rui Ju, Paul S Spencer and K Alan Shore, "The relative intensity noise of a semiconductor laser subject to strong coherent optical feedback", *J. Opt. B: Quantum Semiclass. Opt.* 6, S775–S779 (2004).