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14. ABSTRACT This report results from a contract tasking Dr. Thomas Erneux as follows: The contractor will investigate the modeling of the performance of semiconductor lasers in which both the injected optical signal and the driving current are periodically modulated. Both analytical and numerical studies will be carried out. The contractor will produce a final report detailing the completed analysis and comparing results with published experimental data. In the second phase of the work, optical feedback will be considered. In this case, the rate equations are delay-differential equations. The investigation will concentrate on two Edifferential Cavity mode (ECM) solutions of the laser rate equations, because coupling might lead to high-frequency intensity oscillations. The objective is to determine the conditions for stability of these solutions. Conclusions will be tested by numerical bifurcation studies.					
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Final report:
Contract number: F61775-01-WE036
Bistability of pulsating intensities for double-locked laser diodes

The main objective of this contract was to collaborate with the Nonlinear Optics group at Kirtland Air Force Laboratory. The work started with modulated semiconductor lasers subject to injection, continued on fast pulsating lasers subject to optical feedback, and finished on lasers subject to phase-conjugated feedback. Eight papers listed in the beginning of the reference list are acknowledging the support of AFOSR and resulted from the interactions between Kirtland and Brussels.

1 Modulated lasers

The interest for weakly modulated semiconductor lasers has been revived by experiments using optically injected diode lasers at high injection rates [9, 10]. When a small periodic current modulation is added to the dc-bias current, remarkable limit-cycle phase locking performances have been obtained, producing radiation with high quality microwave sidebands. Such devices are promising for a number of applications that require a spectrally pure microwave oscillator with frequencies in the tens of GHz.

We modeled such a double-locking experiment using the laser rate equations, which are then analyzed by combined analytical and numerical bifurcation techniques. Our objective was to determine simple conditions for bistable pulsating regimes. The modeling and numerical simulations have been done in close collaboration with the group of A. Gavrielides at Kirtland. All analytical work was under the responsibility of T. Erneux at the Free University of Brussels with the help of a Ph.D. student, M. Nizette. Experiments were accomplished by T. Simpson at Jaycor. Funding from EOARD facilitated the interactions between the three groups. A first bifurcation analysis of the problem is proposed in [1]. Several cases of **stable pulsating regimes** were predicted but no case of bistability. The analysis was done for zero detuning and the injection rate was the control parameter. We then concentrated on the non-zero detuning case. Using both the detuning and the injection as control parameters, we showed that **bistability of pulsating regimes** is possible provided that the modulation amplitude is sufficiently high [2]. This is in agreement with the experiments. During our

analysis of the laser rate equations without external modulation, we reexamined older observations by T. Simpson showing **the coexistence of Period 3 and Period 2 regimes**. By using numerical continuation techniques that follow both stable and unstable branches of periodic solutions, we were able to determine the bifurcation diagram of all periodic regimes. We showed that Period 3 regimes correspond to isolated branches of solutions which explain why they were not observed in early experimental studies [3].

The bifurcation possibilities of a single mode semiconductor laser subject to injection became a topic of high interest because it is the simplest problem exhibiting semiconductor laser instabilities in the laboratory. Various groups have tried to simplify the laser equations by using averaging techniques. However, results are limited to small amplitude solutions and require relatively high algebra. By using modern averaging techniques, we were able to determine equations describing the laser bifurcations for solutions of arbitrary amplitude [4]. Furthermore, we tested the asymptotic validity of these equations by comparing numerical bifurcation diagrams.

2 High frequency oscillations

The current interest for semiconductor laser instabilities generating **high frequency oscillations** has led to new activities on semiconductor lasers subject to optical feedback. It is known since 1993 [11] that a **beating between two single external cavity modes** could be possible and that this beating may lead to an efficient pulse source in the microwave (> 20 GHz) region. These regimes are however difficult to achieve in normal conditions because they are dynamically unstable. By taking advantage of recent numerical bifurcation studies [?, 13], we showed that these regimes are more likely to appear for small values of the linewidth enhancement factor α . For α below 1, branches of mixed external cavity modes responsible for the high-frequency oscillations can be fully stable [5]. Our studies on how mixed mode regimes appear in the bifurcation diagram motivated new experiments [14].

The determination of mixed mode solutions benefited from an asymptotic analysis of the Lang and Kobayashi equations [15] for a laser subject to conventional optical feedback (COF) [16]. We then applied the same technique for **lasers subject to phase conjugated feedback (PCF)**.

Phase conjugation is a process in which the light that is reflected back from the phase conjugator has not only its direction of propagation reversed

but also the phase of each of the plane waves components of the optical beam. The most important application of phase conjugation is the correction of optical distortions. In particular, for a distortion that occurs between the source and the phase conjugator, the light retraversing the distortion after reflection from the phase conjugator returns to its original undistorted state. Phase conjugation is used today extensively in lasers to eliminate phase distortions due to heating and stress effects in the laser medium. A second interest of phase conjugation is stability. Phase conjugated feedback (PCF) is preferred over conventional optical feedback (COF) because the full external round trip phase vanishes and the PCF laser cannot lock to an external cavity frequency.

Earlier numerical simulations [18],[21]-[22] and linear stability analyses [19, 20, 24] revealed a rich variety of possible outputs but with little insight on simple bifurcation mechanisms. This has motivated the recent development of numerical continuation methods. In particular, the application of the Matlab package DDE-BIFTOOL [12] has revealed important features of the PCF lasers. Specifically, a **sequence of isolated branches of pulsating intensity solutions** exhibiting simple properties have been found by Green and Krauskopf [17]. In collaboration with Green now at the KU Leuven, we have systematically compared analytical and numerical results. As a result, a simple physical description of the pulsating intensity regimes is possible [7].

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Disclaimer: Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the European Office of Scientific Research, Air Force Laboratory.

2. The contractor, Dr. Thomas Erneux, hereby declares that, to the best of his knowledge and belief, the technical data delivered herewith under Contract No: F61775-01-WE036, is complete, accurate, and complies with all requirements of the contract.

Date: April 6, 2004

Name and Title of Authorized Official: Professor Thomas Erneux

3. I certify that there were no subject inventions to declare as defined in FAR 52.227-13, during the performance of this contract.

Date: April 6, 2004

Name and Title of Authorized Official: Professor Thomas Erneux