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Theoretical analysis of semiconductor ring lasers with short and long time-delayed optoelectronic and incoherent feedback

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ABSTRACT

We report results on the asymptotic, bifurcation and numerical analysis of semiconductor ring lasers with negative optoelectronic feedback or incoherent optical feedback. We find that the dynamical behavior of both systems can be adequately described by two differential equations and one map with time delay on time-scales longer than the relaxation oscillations. On these timescales, the dynamics for both types of feedback is identical. We study the stationary solutions of this model and are able to obtain the analytical expressions of all local bifurcations. As we vary the feedback strength for small delay times comparable to the period of relaxation oscillations, the devices under consideration in the paper display both continuous wave operation and a period-doubling route to chaos. The intensities of two counter propagating modes of both systems exhibit in-phase chaotic behavior similar to single mode semiconductor lasers. However, for long delay times, the counter propagating modes show anti-phase chaotic oscillations. This anti-phase chaotic regime does not involve carrier dynamics and is a result of the bistable character of the semiconductor ring laser.

1. Introduction

Nonlinear dynamics caused by delayed physical mechanisms have been successfully investigated in various areas of science: predator-prey ecosystems [1], blood cell production mechanisms [2], neuronal networks [3], rotating cutting machines [4], satellites distant control [5], etc. Also in optics, delayed optical feedback cannot be fully avoided in experiments. Any optical element placed in front of a laser, such as a detector or even an anti-reflection coated lens, back-scatters part of the laser beam. This retro-reflected light may re-enter in the laser cavity and interfere with the field already existing inside of the cavity. From the point of view of applications the dynamics of delay systems is gaining more and more interest [6]. While initially it was considered more as a nuisance, it is now viewed as a resource that can be beneficially exploited for chaos based communications [7–9], random bit generation [10] and information processing [11,12].

Semiconductor lasers with delayed feedback are known to exhibit a wealth of dynamical behavior, including steady-state continuous wave operation (fixed point dynamics), self-pulsation (limit-cycle dynamics), quasi-periodicity (torus dynamics), frequency-locked (multi-periodic regimes appearing between regions of quasi-periodicity) and chaos with well-known chaotic regimes such as the so-called coherence collapse [13] and low-frequency fluctuation regimes [14]. In particular, a semiconductor laser with coherent optical feedback is the archetypal problem that most investigations have focused almost exclusively. This system seems to exhibit the richest structure and the most complicated dynamics because both the intensity and the phase of the optical field are subject to delayed feedback. With the success of chaotic synchronization such systems have become prime candidates for chaotic communications [15]. A number of experiments have demonstrated the possibility of encoding, transmitting, and decoding information by forcing the receiver to synchronize to the chaotic carrier of the transmitter [7–9]. The primary requirement to achieve such synchronization appears to be that the transmitter and receiver systems be closely matched. This is particularly important in laser systems such as external cavity systems or injection-locked systems, in which the phase of the laser is included in

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the external interaction, and the detuning between transmitter and receiver must be controlled accurately and minimized. Moreover, the linewidth enhancement factor should be closely matched too so that the synchronization remains robust.

An alternative is to design systems in which the phase of the laser is a free parameter and therefore not involved in determining the system's chaotic dynamics. An example of such a system is a semiconductor laser with optoelectronic feedback (OEF) [16] that can be realized if the intensity of the laser field is detected electronically, amplified and then reinjected into the pumping current of the laser. The delay typically arises simply through the propagation time around the feedback loop. Depending on the polarity of the output of the amplifier, OEF through the injection current can be either positive or negative feedback. For both cases, semiconductor laser exhibits regular pulsing, quasi-periodic pulsing and chaotic pulsing states. However, frequency-locked pulsing states are also found in a delayed negative OEF system, but not in a delayed positive OEF system [17]. Recently, chaotic behavior of such a system has also been proposed for application in optical chaos communications [18–20].

Another alternative approach that has been investigated is to consider a semiconductor laser subject to incoherent optical feedback (IOF) [21,22]. In this particular case the system consists of a semiconductor laser whose output field is reinjected into the laser after rotation of the polarization to the orthogonal state, providing a delayed feedback that interacts only with the optical amplifier. In contrast to optoelectronic feedback, this configuration can be implemented using only optical components, and therefore is not subject to electronic bandwidth limitations. Most of the existing studies on the semiconductor lasers subject to IOF or OEF are restricted to the conventional Fabry–Pérot lasers.

The first demonstration of ring-shaped semiconductor laser dates back to 1980 [23]. However, in the early 1990s the idea of integrating semiconductor ring lasers (SRLs) received greater interest. The basic structure of the ring laser has a circular resonator and straight output waveguides. As a consequence of this structure there is no need for reflectors in the laser cavity, what makes it attractive for applications in integrated optics [24]. Different cavity geometries were proposed and demonstrated, such as square mirror based design [25], triangular mirror based design [26], circular, race track cavity with evanescent out-coupling [27], two coupled micro-squares [28], two coupled rings [29], or S-shaped [30] while making use of different waveguides. In a ring-shaped cavity, the situation is totally different from the more common Fabry–Pérot cavity, in which light bounces back and forth between two mirrors. In a ring laser light follows a closed trajectory. A very important consequence of this construction is the simultaneous presence of two counter propagating modes referred to as the clockwise (*CW*) and the counterclockwise (*CCW*) modes. The interaction between the two counter propagating fields is supported by the ring. Both modes are coupled nonlinearly through gain saturation effects and linearly due to localized and/or distributed backscattering. This interaction has been studied in many papers theoretically [31–38] and experimentally [39–41]. SRLs have been recognized to be ideal optical prototypes of nonlinear Z_2-symmetric systems [40], appearing in many fields of physics. This has also led to a renewed purely theoretical interest in SRL.

To the best of our knowledge the nonlinear dynamics of SRL subject to IOF (SRL-IOF) or SRL with OEF (SRL-OEF) has not yet been studied neither theoretically nor experimentally. SRLs with coherent optical feedback have been recently investigated in the literature. In Ref. [42], the authors found experimentally and numerically low frequency fluctuations in SRLs subject to long delay and moderate self-coherent optical feedback. It has been demonstrated that the injection of only one directional mode back into the counter propagating mode leads to square wave oscillations [43]. However, asymmetric cross feedback makes SRL outputs more complex, i.e., chaotic optical signals may be generated in large parameter regions when the feedback is asymmetric [44]. In Ref. [45], the authors considered a chaotic SRL with self optical feedback and investigated both numerically and experimentally its characteristics for fast random bit generation. In Ref. [46] theoretical modeling of chaos-based communication using two chaotic SRLs with asymmetric cross feedback has been reported, and the ON/OFF phase shift keying encryption method was applied. More recently, a hybrid chaos-based communication scheme using three chaotic SRLs has been realized [47].

Our aim in this paper is to investigate theoretically the dynamics of two different SRLs. One laser is subject to negative OEF and the other is subject to IOF. In Section 2, we present the schematics of the systems under study and the mathematical models. In Section 3, we derive a reduced model for both systems by using asymptotic methods. In Section 4, we perform the bifurcation analysis of the stationary solutions of the reduced model. The study of the dynamical behavior of both systems is carried out in Section 5. The final section contains the conclusion of the paper.

2. System configuration and the model

In Fig. 1, we give the schematic representations of two systems under study.

A SRL-OEF is schematically shown in Fig. 1a. In this configuration, a combination of a photodetector and an amplifier is used to convert the optical output of the *CW* mode into an electrical current that is fed back to the SRL through a bias T-circuit. This electrical current may be positively or negatively fed back depending on the polarity of the output of the amplifier in the circuit. In Fig. 1b, a sketch diagram of a SRL-IOF is shown. The system has an external cavity that provides IOF. The *horizontally* polarized *CW* mode beam emitted by the ring is coupled out in the straight waveguide. The first element of the external cavity, the Faraday rotator FR changes polarisation of light to 45°. Then the *CW* mode beam of polarization 45° exits through the polarizer (whose transmission axis is set at 45° to the horizontal) and reflects from a mirror M. Then the reflected beam passes through FR for the second time. Its polarization is rotated by additional 45° and

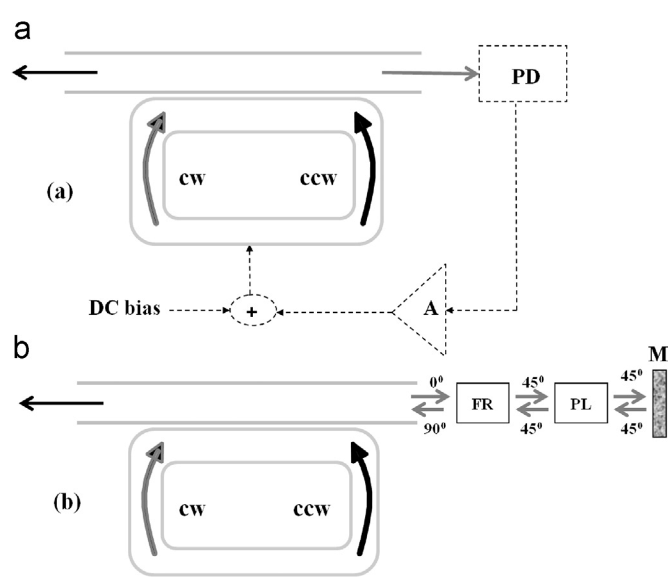

Fig. 1. Schematic representations of (a) SRL-OEF and (b) SRL-IOF. In (a), the solid lines indicate the optical part and the dashed lines the electronic part. PD is the photodetector, A is the amplifier, DC is the direct current, FR is the Faraday rotator, PL-polarizer, M is the mirror.

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