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Effects of quantum noise on the nonlinear dynamics of a semiconductor laser subject to two spectrally filtered, time-delayed optical feedbacks

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ABSTRACT

We report on a theoretical and computational investigation of the complex dynamics that arise in a semiconductor laser that is subject to two external, time-delayed, filtered optical feedbacks with special attention to the effect of quantum noise. In particular, we focus on the dynamics of the instantaneous optical frequency (wavelength) and its behavior for a wide range of feedback strengths and filter parameters. In the case of two intermediate filter bandwidths, the most significant results are that in the presence of noise, the feedback strengths required for the onset of chaos in a period doubling route are higher than in the absence of noise. We find that the inclusion of noise changes the dominant frequency of the wavelength oscillations, and that certain attractors do not survive in the presence of noise for a range of filter parameters. The results are interpreted by use of a combination of phase portraits, rf spectra, and first return maps.

1. Introduction

A semiconductor laser (SCL) subject to feedback has become a paradigm for studying nonlinear dynamics in time-delayed feedback systems. At a fundamental level, studies on such systems are an ideal test bed for delay systems, and at an applied level, some of the dynamical behaviors have been exploited for cryptography, random-bit generation and even understanding of collective neuronal excitations in the brain [1,2] (see references therein). A number of impressive studies on electronic feedback and all-optical feedback, and the resulting dynamics in a SCL have been reported over the years [3,4]. Within the context of all-optical feedback, investigators have studied conventional optical feedback where a mirror is placed in front of the SCL such that a fraction of the light from the laser is reflected back into it [5,6]. Other feedback scenarios have included polarization rotated feedback where the polarization of the feedback light is rotated relative to the dominant polarization mode of the laser light [7–9]. Recently, the effects of injection on the stability properties from two polarization modes have been studied [10].

Another interesting feedback scheme that has been reported is filtered optical feedback (FOF) wherein the feedback light is spectrally filtered before entering the laser [11]. FOF provides the user with two additional parameters, the bandwidth of the filter and the detuning between the filter frequency and the laser light frequency, to control the dynamics of the laser. One of the major dynamical effects observed in FOF is that the frequency of the laser light, for a judicious choice of filter parameters, exhibits controlled oscillations at a frequency that is related to the time delay of the feedback [12]. It has also been shown that for other filter parameters, one can observe a period doubling route to chaos in the frequency of the laser light [13].

Recently, there has been an interest in the dynamics of a SCL subject to two simultaneous FOFs [14,15]. Krauskopf and coworkers have reported an exhaustive study of the bifurcations that arise in such systems [16,17]. The use of two filters provides a number of additional parameters that can be potentially used to control the dynamics of the SCL. Our group reported an experimental study on the frequency dynamics in the light from the laser when subject to two FOFs [18]. Among the more interesting observations was the generation of new frequencies in the system, and the results were explained via a theoretical model that consisted of the usual Lang-Kobayashi rate equations augmented to include two FOFs. The agreement between experiments and theory was excellent.

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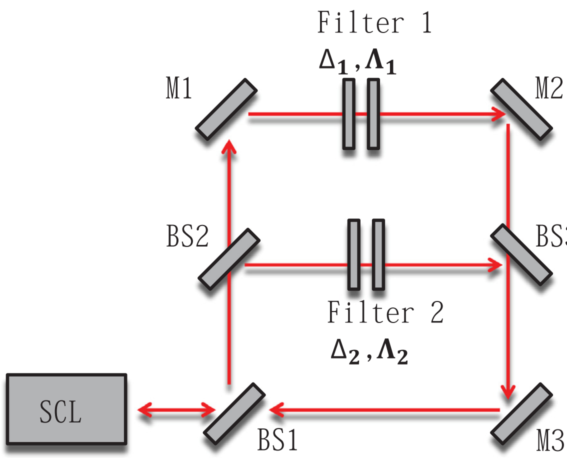

Fig. 1. The schematic shows a semiconductor laser (SCL) subject to optical feedback from two external cavities. The outer cavity (1) is formed by the SCL and the mirrors (M1, M2, and M3). The inner cavity (2) is formed by the SCL, beam splitters (BS2 and BS3), and mirror (M3). Each cavity contains a Fabry–Perot resonator acting as a spectral filter, which can be modified by changing the reflectivity or spacing of the filter mirrors. This in turn changes the bandwidth, Λ. The detuning, Δ, is altered by adjusting the pump current. The delay-times, τ_1 and τ_2, are increased or decreased by lengthening or shortening the cavities.

Table 1
The parameter values for a typical SCL which are used in the simulations (unless otherwise specified).

Quantity	Symbol	Value
Linewidth enhancement factor	α	5
Feedback rate field 1	κ_1	Varies
Feedback rate field 2	κ_2	0.8 GHz
Bandwidth of filter 1	Λ_1	Varies
Detuning of filter 1	Δ_1	Varies
Bandwidth of filter 2	Λ_2	1.0 GHz
Detuning of filter 2	Δ_2	−1.5 GHz
Delay-time field 1	τ_1	14.28 ns
Delay-time field 2	τ_2	7.93 ns
Phase accumulation	θ	1.111
Differential gain coefficient	ξ	$5 \times 10^3\ s^{-1}$
Photon decay rate	Γ_0	$10^{11}\ s^{-1}$
Carrier lifetime	T_1	1 ns
Threshold pump rate	J_{thr}	$1 \times 10^{17}\ s^{-1}$
Pump rate	J	$1.5 J_{thr}$
Spontaneous emission rate	R_{sp}	$5 \times 10^{12}\ s^{-1}$
Shot noise diffusion rate	D	$1.45 \times 10^{16}\ s^{-1}$

One of the observations that emerged from our prior work was that the frequency of laser light in a SCL subject to two FOFs follows a period-doubling route to chaos. However, the feedback strength necessary for coherence collapse that was predicted by the theoretical model was higher than what was observed experimentally. This mismatch between theory and experiment inspired us to examine the role of unavoidable quantum noise in the laser and its influence on the dynamics of the laser. To this end, we have augmented the theoretical model with Langevin noise terms to account for the spontaneous emission noise as well as inversion noise. To give one a picture of the system studied, we show a schematic of the experimental design [Fig. 1] highlighting the key parameters accessible to experiment, which are detailed in the following section.

2. Model

A semiconductor laser with FOF from a single cavity can be modeled with a set of rate equations describing the time evolution of the slowly varying complex electric fields, $E(t)$ and $F(t)$, of the laser and feedback field, respectively, and the carrier inversion $N(t)$ [11]. Our setup [Fig. 1], which includes two cavities, each with a spectral filter, must therefore include two filtered feedback fields, $F_1(t)$ and $F_2(t)$, resulting in the following description,

$$\frac{dE}{dt} = \frac{1}{2}(1 + i\alpha)\xi N(t)E(t) + \kappa_1 F_1(t, \tau_1) + \kappa_2 F_2(t, \tau_2) + L_E(t), \tag{1a}$$

$$\frac{dN}{dt} = J - J_{thr} - \frac{N(t)}{T_1} - [\Gamma_0 + \xi N(t)]|E(t)|^2 + L_N(t), \tag{1b}$$

$$\frac{dF_1}{dt} = \Lambda_1 E(t - \tau_1)e^{-i\omega_0\tau_1} + (i\Delta_1 - \Lambda_1)F_1(t). \tag{1c}$$

$$\frac{dF_2}{dt} = \Lambda_2 E(t - \tau_2)e^{-i\omega_0\tau_2} + (i\Delta_2 - \Lambda_2)F_2(t), \tag{1d}$$

where ξNE in the first term of Eq. (1a) accounts for the growth (or decay) when the carrier inversion $N(t)$ is above (or below) threshold, and ξ is the differential gain coefficient. α is the

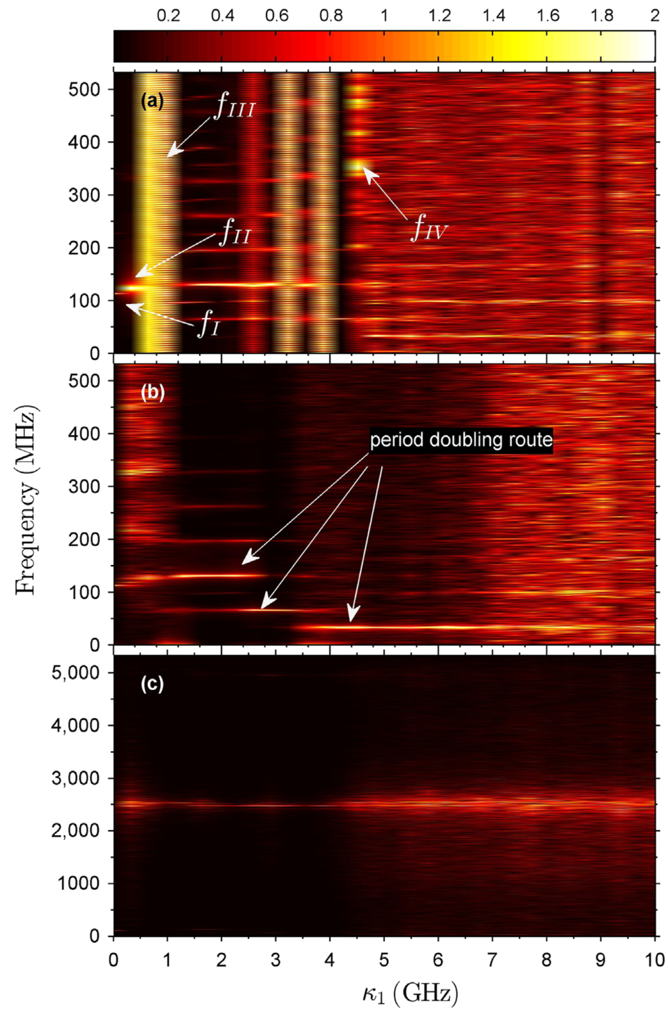

Fig. 2. Deterministic (a) and stochastic [(b), (c)] density plots of the period doubling route to chaos when the feedback strength κ_1 from cavity 1 is increased. The bandwidth and detuning are fixed at $\Lambda_1 = 1$ GHz and $\Delta = -0.5$ GHz, otherwise all other parameters are recorded in Table 1. f_{I-IV} are the frequencies discussed in this text which differ significantly in the stochastic period doubling route. Note that (c) contains the stochastic spectra extended out to 5 GHz.