Semiconductor laser under resonant feedback from a Fabry-Perot resonator: Stability of continuous-wave operation

V. Z. Tronciu

Department of Physics, Technical University of Moldova, Stefan cel Mare av. 168, Chisinau MD-2004, Republic of Moldova

H.-J. Wünsche

Institute of Physics, Humboldt-University Berlin, Newtonstr. 15, 12489 Berlin, Germany

M. Wolfrum and M. Radziunas

Weierstraß-Insitut für Angewandte Analysis und Stochastik, Mohrenstraße 39, 10117 Berlin, Germany

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We study the continuous-wave (cw) operation of a semiconductor laser subject to optical feedback from a Fabry-Perot resonator in a case where the emission is resonant to a reflection minimum of the resonator. This configuration is treated in the framework of Lang-Kobayashi equations. The nature of bifurcations and the stability of steady state solutions is analyzed in terms of the dependence on magnitude and phase of the feedback. In contrast to conventional optical feedback from a single mirror, the locus of external cavity modes is not elliptic but represents a tilted eight with possible satellite bubbles. Below a critical feedback strength, which is analytically given, only one single mode exists representing the completely unchanged cw emission of the laser. In this weak-feedback regime, the feedback phase allows noninvasive control of the cw emission and a tailoring of its small-signal response within wide limits. The results obtained are a prototype for all-optical realizations of delayed feedback control.

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I. INTRODUCTION

Stabilization of laser emission by external cavities is long established [1–4] and of continuous interest [5,6]. Fabry-Perot (FP) cavities are mostly operated as optical filters, which suppress all waves which do not fit in the narrow spectral resonances [3–5]. The only exception, to our knowledge, is the powerful Pound-Drever-Hall technique [2], which exploits a resonant minimum of the FP reflectivity in order to derive an electronic control signal used to lock the laser cavity to the FP resonance.

In contrast to all these methods, we consider stability control by direct optical feedback from an FP with mirror-reflectivity R and round trip time τ_{FP} (Fig. 1). Under ideal conditions, in particular no loss and equal phase and group velocities, the feedback field is

$$\mathcal{E}_{\mathrm{b}}(t) = K\sum_{n=0}^{\infty} R^n \cdot [\mathcal{E}(t_n) - \mathcal{E}(t_n - \tau_{\mathrm{FP}})]. \quad (1)$$

$\mathcal{E}(t)$ represents the field amplitude emitted by the laser. $t_n = t-\tau_l - n\tau_{\mathrm{FP}}$ is delayed by n round trips in the resonator plus the round trip time τ_l between laser and resonator. K measures the magnitude of feedback, including a possible attenuation between FP and laser.

We focus on a case where the laser without feedback is assumed to emit continuous wave (cw) with a single frequency ω_0 resonant to the FP, i.e., $\omega_0\tau_{\mathrm{FP}}$ is an integer multiple of 2π. In this particular case, $\mathcal{E}$ is τ_{FP}-periodic and the feedback field $\mathcal{E}_{\mathrm{b}}$ becomes zero. Thus, the free running state of the laser is not modified by the presence of the resonant FP. One might wonder whether the resonator has any influence at all. However, perturbations and noise cause deviations from the ideal state giving rise to a nonzero feedback, which in turn modifies the response of the laser to the perturbations. Thus, the considered feedback configuration does not change the laser state itself but its stability properties.

Delayed feedback of type (1), originally introduced by Pyragas and Socolar [7–9], is well known as a general and self-adaptive method for noninvasive control of dynamical systems. Delayed-feedback control (DFC) has been widely used to stabilize unstable periodic orbits within chaos [7–10]. It is also able to improve the coherence of oscillatory motion under the impact of noise [11,12]. Very recently, DFC has successfully been used to control the stability of equilibria [13].

Already one decade ago, Socolar *et al.* [8,9] noticed that feedback from a FP should allow an all-optical implementation of this general control scheme. Surprisingly, no in-depth study of such an implementation exists until now, although the first numerical explorations [14–16] of similar interferometric configurations gave examples for the possibility of an all-optical chaos control. The lack of progress is supposably related to the multiple time scales being specific for all-optical configurations [14]. They range over more than six orders of magnitude from the femtoseconds of the optical oscillations over hundreds of picoseconds for inversion oscillations up to round-trip cycles of several nanoseconds in the long-cavity configurations considered in Refs. [14–16]. In contrast to other applications of the Pyragas-Socolar schema, oscillations on longer time scales are to be controlled here with an interferometric feedback that is sensitive to the shorter time scales, too. Indeed, using the standard scaling $\mathcal{E}(t) = \mathrm{Re}\{E(t)\exp(i\omega_0 t)\}$ onto slowly varying amplitudes $E(t)$, Eq. (1) transforms to

