

Feedback phase sensitivity of a semiconductor laser subject to filtered optical feedback

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Filtered optical feedback (FOF) can be used to stabilize a semiconductor laser but also to generate chaotic laser emission that may find applications in chaos communication schemes. We study theoretically the dynamics the FOF laser and identify the feedback phase as an important parameter that organizes the huge degree of multi-stability in this system. A systematic experimental study of the phase effect on the dynamics is presented that is supported by theoretical findings.

Recent research in laser dynamics goes towards harnessing the nonlinear dynamical properties of semiconductor laser for new applications. Secure communication with chaotic carrier waves [1] or broad band laser sources [2] are only two examples of this vital field of nonlinear laser dynamics. A key to successfully exploiting nonlinear laser dynamics is to understand the underlying mechanisms which lead to the unstable behavior of semiconductor lasers, and to gain control over them.

Here we investigate the underlying structure of a semiconductor laser subject to filtered coherent optical feedback (FOF). First experimental and theoretical studies of the FOF laser as considered here can be found in Ref. [3; 4]. In particular in Ref. [5] the key role of the feedback phase C_p for organizing the dynamics of the FOF laser was demonstrated theoretically. In order to verify the relevance of C_p the following experiment was designed; a sketch is shown in Fig. 1. The laser is a commercially available single mode Fabry-Pérot type semiconductor laser emitting at 780 nm with a threshold current of $I_{th} = 43$ mA. Throughout the experiments the laser was operated at a pump current of $I = 70.6$ mA. The temperature of the lasers can be stabilized with an accuracy in the order of 0.01 K. The laser's frequency shift due to changes of the pump current was linear and was estimated as 3.6 GHz/mA. The filter consists of two flat mirrors with reflectivity $R = 70$ %, respectively. The distance between the mirror was $D = 3.9 \pm 0.1$ cm, which results in a free spectral range of $FSR = 3.8 \pm 0.1$ GHz. The finesse was measured experimentally as $f = 5 \pm 0.5$, which results in a filter width of $HWHM = 385 \pm 30$ MHz (half width at half maximum). Importantly, the piezo translation stage with a mechanical resolution of 20 nm allows for changes of the feedback phase with a resolution of 19 measurement points per 2π -cycle. The FOF laser was operated with very low feedback, the threshold reduction is less than 0.1 %. The feedback was controlled with a combination of a polarizer and a $\lambda/2$ -plate. Finally, in total four optical isolators, with isolation better than -30 dB each, ensure clockwise propagation of the light in the feedback loop and prevent from unwanted reflections.

Figure 2 shows experimental measurements of the underlying mode structure of the FOF laser and its dependence on the detuning Δ and the feedback phase C_p . For each panel the pump current of the laser is modulated slowly with ramp and the intensity I_F of the feedback field is monitored. Increasing and decreasing parts of the pump current ramp are shown in each panel of Fig. 2. Small changes of the pump current result in a slight change of the laser frequency and therefore, in a change in the detuning between the center frequency of the filter (which is kept fixed) and the frequency of the solitary laser. Because the modulation frequency and the modulation amplitude is small, other effects can be neglected. First, we concentrate on the effect of changing detuning in Fig. 2(a). There is a maximum in I_F around zero detuning, where the laser frequency coincides with the center frequency of the filter. As the pump current changes the feedback intensity I_F changes discontinuously. Plateaus can be seen where I_F is almost constant, interrupted by sudden jumps. On each plateau the feedback intensity I_F stays almost constant because the FOF laser locks to a stable mode with almost constant frequency; we call this modes external filtered modes (EFMs). When such a mode becomes unstable or disappears the FOF laser jumps to the next adjacent EFM. Approximately 10 EFMs are found when the laser frequency is scanned over the whole filter profile. Due to hysteresis effects the situation for increasing and decreasing pump current differs quantitatively. Figure. 2(b) shows the same situation for slightly increased value of the feedback phase C_p . In particular in can be seen that the plateaus for increasing pump on the left filter flank are shifted downwards slightly, while they are shifted upwards on the right filter flank. The reverse happens for decreasing pump current. This is indicated by the arrows in the individual panels. For increasing changes of C_p the EFMs shift continuously [Fig. 2(b) to (f)]. When C_p has changed by 2π the situation of Fig. 2(a) is retained. Between each panel C_p has changed by approximately $1/3\pi$.

We model the FOF laser with a set of rate equations for the complex envelope of the laser field E , the filter field F , and the laser inversion N given by

$$\dot{E} = (1 + i\alpha)N(t)E(t) + \kappa F(t, \tau) \quad (1)$$

$$T\dot{N} = P - N(t) - (1 + 2N(t))|E(t)|^2 \quad (2)$$

$$\dot{F} = \Lambda E(t - \tau)e^{-iC_p} + (i\Delta - \Lambda)F(t). \quad (3)$$

Here $\alpha = 5$ is the self-phase modulation parameter, $\kappa = 0.0001$ the feedback rate, $T = 100$ the electron decay rate, $P = 2.55$ the pump rate, C_p the feedback phase, $\Delta = -0.014$ the filter detuning and $\Lambda = 0.014$ the filter width (HWHM). Note that the detuning is defined

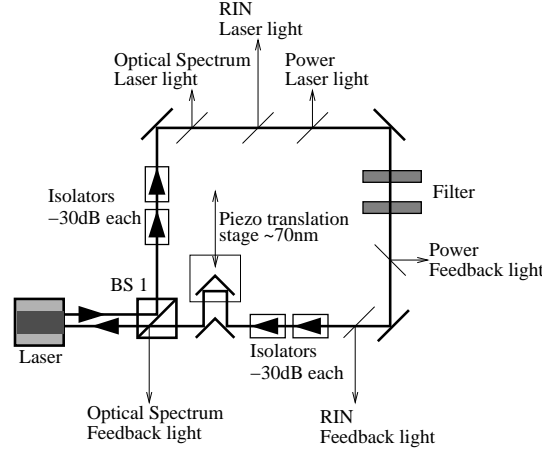


Figure 1: Setup of the FOF laser with the Fabry-Pérot filter, piezo translation stage, optical isolators. The detection for both the laser field and the feedback field consists of scanning Fabry-Pérot interferometer, fast photo diodes, electrical spectrum analyzer, digital oscilloscopes, and slow photo diodes.

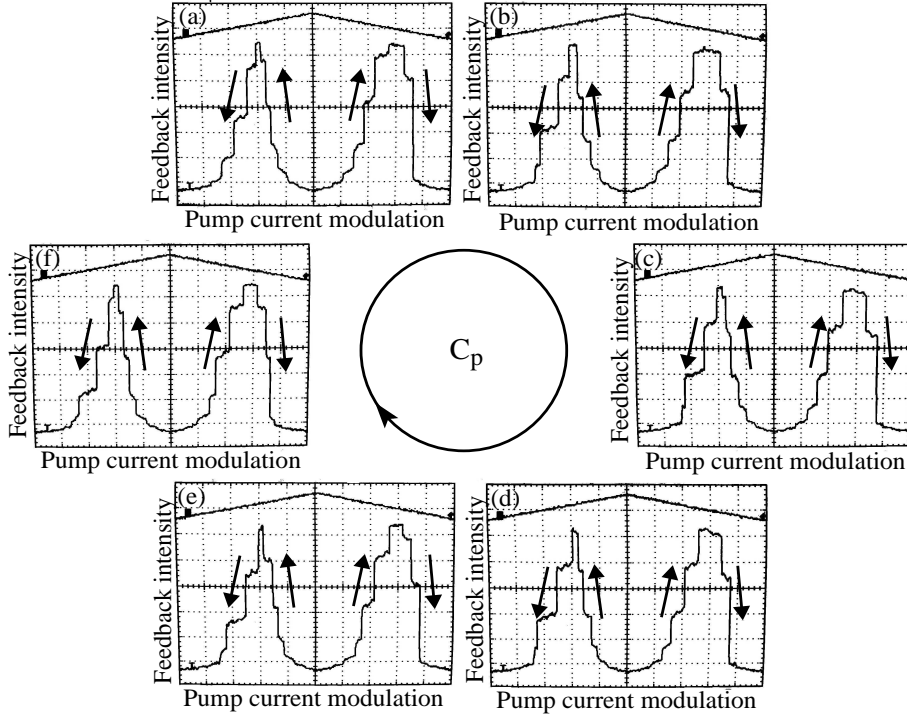


Figure 2: 2π -cycle of the EFMs. Each panel shows the intensity of the feedback light as a function of increasing and decreasing pump current. The pump current was slowly modulated with a triangular ramp, which is shown in the top part of each panel.

as $\Delta = \Omega_F - \Omega_0$, where Ω_0 solitary laser frequency and Ω_F the center frequency of the filter.

The external filtered modes are the basic solution of Eqs. (1)–(3) are CW states, with a frequency deviation ω_s from the solitary laser frequency at threshold. The amplitudes of the laser field $\sqrt{I_L}$ and the filtered feedback field $\sqrt{I_F}$ and the inversion N_s of laser are constant in time. The feedback field may have a constant phase shift ϕ .

$$E(t) = \sqrt{I_L} e^{i\omega_s t}, N(t) = N_s, F(t) = \sqrt{I_F} e^{i\omega_s t + i\phi}. \quad (4)$$

In what follows we use numerical continuation [6] to investigate the structure and stability of the EFMs as a function of the solitary laser frequency Ω_0 and the feedback phase C_p . This is shown in Fig. 3, where in each panel the feedback intensity I_F is plotted as a function of Ω_0 , and C_p takes the values indicated in the panels. As Ω_0 is changed, EFMs are born and destroyed in saddle-node bifurcations (+). In particular, the thick curves indicate stable EFMs which can be seen in the experiments. Once a stable EFM is lost in a saddle-node bifurcation (together with an unstable EFM) the FOF laser jumps to the adjacent stable EFM. For each value of Ω_0 more than one stable EFM can be found. This leads to hysteresis effects in for increasing and decreasing Ω_0 . Moreover the EFMs change their position as the feedback phase C_p is changed, which is indicated by the arrows in each panel. Indeed in light gray curves of saddle-node bifurcations are plotted, as parameterized by the feedback phase.

In conclusion, we analyzed the external feedback modes of the FOF laser experimentally and theoretically. In particular the experimental design allowed to study the influence of the feedback phase. The experimental results could be reproduced in good agreement

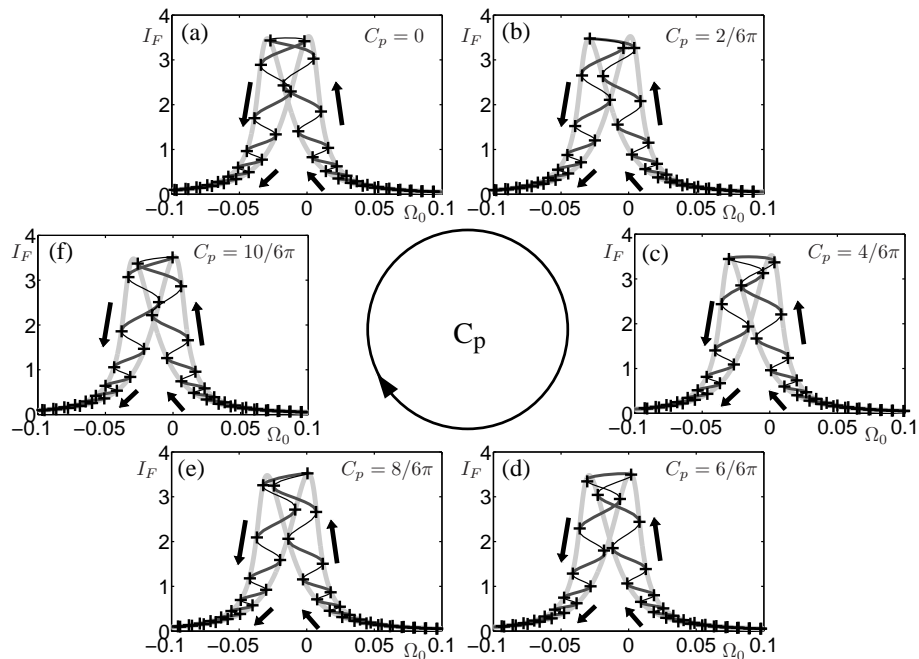


Figure 3: 2π -cycle of the EFMs as computed from Eqs. (1)–(3). Each panel shows the intensity of the feedback light as function of Ω_0 . Unstable parts are black, stable parts are dark gray and saddle-node bifurcations are indicated as (+). The light gray line is the saddle-node bifurcation line parameterized by C_p .

by studying a rate equation model. This is the foundation for current experimental and theoretical studies focusing on complex dynamics, for example those arising from Hopf bifurcations of EFMs for higher feedback rates.

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