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Filtered Optical Feedback Induced Frequency Dynamics in Semiconductor Lasers

Alexis P. A. Fischer,1 Mirvais Yousefi,2 Daan Lenstra,2,3 Michael W. Carter,4 and Gautam Vemuri4

1Laboratoire de Physique des Lasers, Université Paris XIII, UMR CNRS 7538, Paris, France
2Vrije Universiteit Amsterdam, 1081 HV Amsterdam, The Netherlands
3Research Institute COBRA, Technical University Eindhoven, Eindhoven, The Netherlands
4Indiana University-Purdue University Indianapolis, Indianapolis, Indiana 46202-3273, USA

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We demonstrate experimentally and numerically that, by spectrally filtering the delayed optical feedback into a semiconductor laser, one can elicit novel dynamics in the frequency of the laser output light on a time scale that is set by the delay time of the feedback. In particular, we show that through a judicious choice of the filter bandwidth, and its frequency relative to that of the laser, one can produce controlled oscillations in the frequency of light from the laser.

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A diode laser with feedback is a basic paradigm for studying nonlinear dynamics in delayed feedback systems and, hence, has been intensely investigated in recent years [1–3]. At a fundamental level, these investigations are an ideal test bed for laboratory studies of delay systems [3,4]. At an applied level, some of the dynamical behaviors, such as chaos in intensity of light, have been exploited for cryptography [5]. However, to realize such applications in practice, there is a need for robust control techniques that are external to the laser and which can be used to elicit a desired dynamical response from the laser. Filtered optical feedback (FOF), where the filter alters the spectral content of the feedback light, provides precisely this kind of control mechanism [6]. A filter, because of its nonlinear transmission function, introduces a controllable nonlinearity in the feedback system, and its influence on the laser dynamics can be manipulated via the filter’s bandwidth, and its detuning from the laser frequency.

FOF offers several advantages over unfiltered, or conventional, optical feedback (COF), e.g., an alteration of the feedback strength can be accomplished by changing the detuning between the laser and filter, instead of introducing attenuating optics in the feedback path. More importantly, we demonstrate in this Letter, for the first time, that one can exploit the interplay between the nonlinear response of the filter and the a parameter of the laser, to induce novel dynamics in the frequency of the light from the laser. We also show that the time scale of the induced frequency dynamics is dominated by the feedback-delay time, unlike COF-induced intensity dynamics where the time scale is mostly dominated by the relaxation oscillation (RO) frequency ($\nu_{\text{RO}}$) of the laser. The origin of frequency dynamics can be qualitatively motivated by recognizing two facts; first, that a filter alters the intensity of the light through it based on the frequency detuning between the incident light and the center frequency of the filter, and, second, that the frequency of light from a diode laser is redshifted by an amount proportional to the intensity of incident light. One can loop the filter and the laser together and, by choosing an appropriate operating point on the filter transmission function, induce controlled frequency oscillations.

Based on the relative values of the filter bandwidth ($\Delta \nu_{\text{ECM}}$), the external-cavity mode (ECM) spacing ($\Delta \nu_{\text{ECM}}$), and the RO frequency $\nu_{\text{RO}}$, one can divide the FOF induced dynamics into three regimes; large, intermediate, and narrow filter cases. If the filter bandwidth is much larger than the other two, the dynamics are very similar to those due to COF. If the filter bandwidth is the smallest of the three, then there will be only one ECM within the filter profile and the laser tends to operate on that mode. The most interesting regime from a dynamical perspective, and, hence, the one emphasized in this Letter, arises when the filter bandwidth lies between $\nu_{\text{RO}}$ and $\Delta \nu_{\text{ECM}}$. Since the complexity of the dynamics depends on the number of available ECMs, this regime creates a situation where the dynamics are more complex than with a narrow filter, and yet not dominated by the RO frequency.

We note that some recent reports have used optoelectronic feedback to produce nonlinear dynamics in the frequency of light from a semiconductor laser, and also demonstrated message encryption by synchronizing the chaotic output of two such lasers [7]. The emphasis in our work is quite different, viz. a demonstration that one can produce novel frequency dynamics on a time scale that is determined by the optical delay of the feedback light. Furthermore, in contrast to Ref. [7], where the feedback is incoherent, our work reports on an all-optical mechanism, and is an example of coherent feedback. Coherent feedback permits one to, potentially, control the number, and position, of the ECMs within the filter profile, and thereby manipulate the laser dynamics. We also note that other recent works have utilized frequency selective optical feedback from a diffraction grating to study the influence of such feedback on the low frequency fluctuation dynamics of a semiconductor laser, with an emphasis...
on elucidating the multimode dynamics that result in such systems [8].

In a previous theoretical paper, the variety of dynamics that arise during FOF [9] are discussed. In the present Letter, we will focus on the experimental demonstration of a particular type of dynamics, viz. controlled oscillations in the instantaneous optical frequency. Such a device is an all-optical analog of electronic voltage-controlled oscillators and may find many applications. The instantaneous frequency oscillations can be qualitatively explained in the following way: In the first approximation, the power emitted by the laser is constant, whereas the amount of light reflected by the filter depends nonlinearly on the frequency of the laser. When the solitary-laser frequency is tuned to the blue wing of the filter, the frequency of the external-cavity laser shifts towards the filter center frequency (i.e., the frequency at which maximum feedback occurs), due to the feedback induced redshift associated with the $\alpha$ parameter. In principle, this could bring the laser to a cw state of operation near the filter center frequency. However, this state is not stable anymore, because it has been destabilized by a Hopf bifurcation due to the large feedback strength available at the filter center [9,10]. Instead, the RO are undamped, whereafter, because the width of the filter is less than the RO frequency, the effective feedback rate reduces. This reduction in feedback rate is accompanied by a blueshift, thus bringing the external-cavity laser system back to the starting situation. This scenario repeats periodically with a period corresponding to the round-trip time. Very recently, Erneux has reconfirmed the existence of this Hopf bifurcation for filtered feedback through an asymptotic analysis based on the laser rate equations [10].

Figure 1 is a schematic of the experiment which consists of a single-mode, 5 mW Fabry-Pérot–type semiconductor laser emitting at 780 nm, with a threshold current of 46 mA (free running) and an external-cavity loop that contains a filter and a diagnostic branch. The external-cavity loop also has a neutral-density filter ND, a beam splitter BS1, and the spectral filter. The filter consists of two mirrors, M1 and M2, spaced by a distance $d$ and has a finesse $f$, while the distance between the laser and M1 is $L$. M1 and M2 are 3 mm thick, wedged mirrors to minimize multiple reflections inside the mirrors. Both mirrors are fixed on accurate, fine-tuning mechanical mounts to facilitate the alignment of reflected light into the laser. The diagnostic branch consists of arms A, B, C, D, and E, which are isolated from the rest of the setup by optical isolators I1, I2, and I3, respectively. Arm A consists of a scanning 250 MHz free spectral range (FSR) Fabry-Pérot interferometer (FPI) with a finesse of 25 and a photodiode PDA, and is used to measure the optical spectrum with a resolution of 10 MHz. Arm B has a 1 GHz bandwidth photodiode PDB with a 30 dB amplifier, and measures the direct output power of the laser. Arm C consists of a diagnostic filter that converts the instantaneous frequency of the laser into power that is detected by a 1 GHz bandwidth photodiode PDC. The linewidth of this diagnostic filter is governed by a tradeoff between covering the full frequency range of the laser and achieving maximum sensitivity in converting frequency changes into power. In practice, the diagnostic filter bandwidth is chosen 2 to 5 times larger than the width of spectral filter. Arms D and E consist of 1 GHz bandwidth photodiodes. The light transmitted through the spectral filter is measured in arm D with PDD while light reflected by the filter is detected by PDE.

The RO frequency of the laser was about 4–5 GHz and the external-cavity round-trip path length was typically 6 m, resulting in an ECM spacing of 50 MHz. The spacing between the filter mirrors was $d = 2.1$ cm, with a finesse $f = 10$, implying a filter FSR of 7 GHz and a bandwidth (FWHM) of $\delta \nu_f = 700$ MHz, leading to several ECMs within the filter bandwidth. To demonstrate the principal results of this work, i.e., the occurrence of round-trip oscillations in frequency, we show in Fig. 2 a time series...
of the variations in the frequency, as detected by PDC after a frequency to power conversion by the diagnostic filter. This was obtained for a fixed pump current, chosen such that the solitary-laser frequency was about 200 MHz higher than the filter frequency. Figure 2 shows that the instantaneous frequency of the laser oscillates with a period (τ) of 19.6 ns. This is in agreement with a round-trip delay of 6 m and, hence, provides direct evidence for our contention that a suitable choice of the filter bandwidth, and its detuning from the laser, can be used to produce frequency dynamics on the time scale τ. At the same time, the measurements on PDB showed no evidence of oscillatory behavior of the power. The only power variations detected were noiselike which are responsible for the irregular amplitudes of the signal in Fig. 2.

The period of the frequency modulation signal, measured as a function of the external-cavity length, is shown in Fig. 3. The linear dependence confirms that these frequency dynamics are feedback-delay induced and that for these dynamics the ROs play a marginal role. For wide filters, such frequency oscillations do not arise since the dynamics are then dominated by RO. Narrow filters also do not permit frequency oscillations because the filter blocks the feedback for oscillations at frequencies higher than its bandwidth [9].

We emphasize the necessity of the filter in inducing the frequency-periodic solutions described by Eq. (1) through the following theoretical consideration, based on the rate equations of Ref. [9]. Quite generally, the feedback field can be expressed as

$$F(t) = F_0(t)e^{i\delta t + i\rho(t)},$$  \hspace{1cm} (2)

where $F_0(t)$ and $\rho(t)$ are the time-dependent amplitude and phase, and we assume that both are periodic in time with period τ. In absence of the filter, i.e., in case of COF, $F(t)$ would be proportional to the time-delayed version of Eq. (1), implying $F_0 = \sqrt{P}$; i.e., $F_0$ would be time independent. On the other hand, using the general rate equations (1–3) of Ref. [9], it is straightforward to show that

$$F_0(t) = -\frac{\sqrt{P} \xi n}{2\gamma \cos[\rho(t) - \varphi(t)]},$$  \hspace{1cm} (3)

where $\xi$ is the gain coefficient, $\gamma$ is the feedback rate at the center frequency of the filter, and $n$ is the carrier inversion [9] for the solution (1), whose precise value is not relevant here, except that it is time independent. Without a filter, we would have (see [9]) $\rho(t) = \varphi(t) - (\omega_0 + \delta) t$, and this leads to the usual stationary state solution in case of COF. Hence, only with the filter present can one expect a nontrivial solution of the form (1) and (2) to exist.

The experimental observation of laser frequency oscillations with a period of τ is well reproduced numerically by the rate-equation model for FOF described in Ref. [9]. We found, under similar conditions as in the experiment, viz. filter bandwidth FWHM of 700 MHz and a feedback rate not exceeding 10^9 s⁻¹, i.e., large enough to have several ECMs within the filter profile, that the prevailing dynamics are oscillations in the laser frequency at round-trip time periodicity. This happens in a sizable interval of solitary-laser frequencies on the blue side of the filter. An

![FIG. 3 (color online). Experimentally measured period of the laser frequency oscillations as a function of the external delay, showing the linear dependence of the period on the delay.](image-url)

![FIG. 4. Calculated time series of the instantaneous frequency fluctuations for τ = 10 ns. The 11.3 ns period is in good agreement with the 11.4 ns that the light spends externally.](image-url)
example of a frequency oscillation at $\tau = 10$ ns is seen in Fig. 4. The amplitude of these oscillations is roughly equal to 800 MHz, which is indeed to be expected at the current feedback rate ($\sim 1$ GHz), as can be concluded from Fig. 3 of Ref. [9].

The accompanying oscillations in the power (not shown) remain smaller than 1% of the average output power. The oscillation period is 11.3 ns, more than 10% higher than the external delay time of 10 ns, which is explained by the additional time $1/\Lambda = 1.4$ ns spent by the light in the filter. The simulations were performed using the same code as in Ref. [9]. Parameter values are linewidth enhancement factor 5, feedback rate $0.981 \times 10^9$ s$^{-1}$, external round-trip time 10 ns, gain coefficient $5.0 \times 10^3$ s$^{-1}$, photon decay rate $1.0 \times 10^{11}$ s$^{-1}$, carrier recombination rate 1.0 ns, pump rate 50% above threshold, and threshold pump rate $1.4 \times 10^{17}$ s$^{-1}$.

In summary, we have demonstrated that by spectral filtering of the delayed optical feedback into a diode laser it is possible to induce controlled oscillations in the instantaneous frequency of light from the laser. This requires a judicious choice of the filter bandwidth and the DL frequency with respect to the central filter frequency. Furthermore, we have shown that, for intermediate filter widths, one can mitigate the effects of RO and ensure that the dynamics are on a time scale that is due to the external delay. We have demonstrated these by developing an all-optical frequency oscillator. It is important to mention that we have also done similar experiments in a configuration where the external delay is a ring cavity. The results are identical to those presented here, indicating that the frequency oscillator is a delay induced dynamical device. Last, we note that the simulations of Ref. [9] indicate that, with some refinements to the experiment, notably with different feedback rates, one can induce other nonlinear dynamical responses in the frequency of the laser, such as period doubling and chaos, which can be exploited for signal routing and other telecom applications.

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