Dynamics in the Frequency of a Semiconductor Laser using Feedback from a Narrow Filter

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We demonstrate 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.

Diode lasers subject to external optical feedback have been intensely studied, both theoretically and experimentally [1-4]. From a technological point of view, it is essential to understand and control the feedback laser, since feedback occurs naturally in any application, such as back reflections from a fibre facet, and thus must be confronted and understood. From a more fundamental point of view, the feedback laser is an example of a delayed dynamical system and its understanding may contribute to furthering our knowledge of many other delayed systems, which occur frequently in nature.

The laser with feedback from an external cavity is known to show a wide range of dynamics [1][3][4]. Unfortunately, there are very few and sometimes inaccessible control parameters, which dictate the dynamics and thus the resulting analysis requires pain-staking accuracy. Recently, we proposed the use of a frequency filter in the external cavity by means of which one may control many aspects of the feedback light and thus influence the feedback system [5]. There two additional control parameters introduced by the filter: its spectral bandwidth and the position of its central frequency relative to the solitary (stand alone) laser frequency, can be used to alter the feedback light such that desired dynamics may be achieved.

In this paper, we present a study of the laser with frequency filtered external optical feedback and identify a novel type of dynamics that occur in the frequency of the output light, which is achieved by a judicious choice of the filter bandwidth and its detuning from the solitary laser frequency. Generally, the filtered feedback can be classified into three different regimes [5], depending on the ratio of the filter bandwidth Λ, the inverse of the external cavity roundtrip time τ^{-1}, and the relaxation oscillations (RO) frequency ν_{RO}. If Λ is larger than ν_{RO}, then the feedback light will be (almost) unaffected by the filter and the system will show standard conventional optical feedback (COF) dynamics. If Λ is smaller than ν_{RO}, but larger than τ^{-1}, the system will be within the filtered feedback (FOF) regime and the dynamics may vary substantially from the corresponding COF dynamics. Finally, if Λ is smaller than both ν_{RO} and τ^{-1} the dynamics will predominantly be dictated by the filter. Our focus will be on the intermediate filter case, where several external cavity modes (ECMs) exist within the bandwidth of the filter, i.e. $\Lambda\tau > 1$ and $\Lambda < \nu_{RO}$. The nonlinear properties of the filter, in combination with the internal non-linearity of the laser as described by the α–factor, will produce a novel type of dynamics that produce oscillations in the frequency of the output light on the external cavity roundtrip timescale, while keeping the power variation below the detection limit. Due to lack of space, here we will only present the experimental results, while for a complete analysis of the phenomenon we refer to [6].

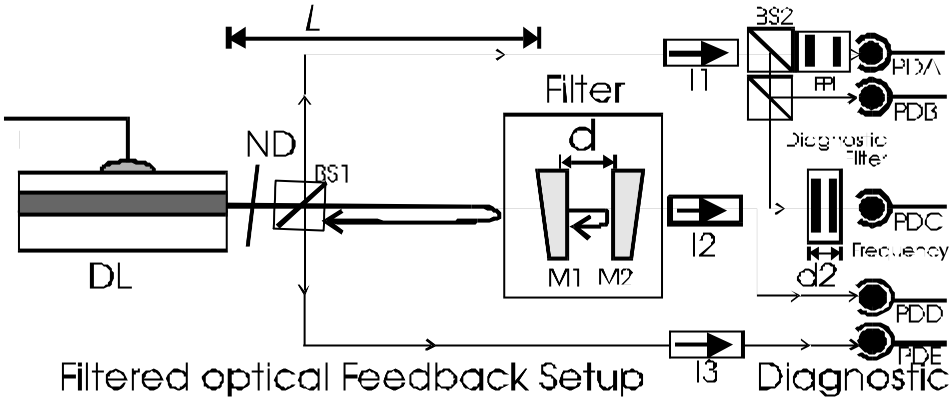

Fig. 1. Schematic of the setup. DL : Diode laser, ND : tunable neutral density filter, M1, M2 mirrors of the filter, I1,I2,I3: optical isolators, BS1, BS2, BS3 : Beam splitters, PDA, PDB, PDC, PDD,PDE : Photodiodes, FPI: Fabry-Pérot interferometer.

Fig.1 is a schematic of the experiment which consists of a single-mode, 5mW Fabry-Pérot type semiconductor laser emitting at 780nm, 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 NF, a beam splitter BS1, and the spectral filter F. 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 3mm 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 set-up by optical isolators I1, I2, and I3 respectively. Arm A consists of a scanning 250MHz 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 30dB 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 trade-off 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 filter F. Arms D and E consist of 1 GHz bandwidth photodiodes. The light transmitted through F is measured in arm D with PDD while part of the light reflected by F is detected by PDE.

The RO frequency of the laser was about 4-5 GHz and the external-cavity roundtrip path length was typically 6m, resulting in τ^{-1}=50 MHz. The spacing between the filter mirrors was *d*=2.1 cm, with a finesse *f*=10, implying a filter FSR of 7GHz and a bandwidth (FWHM) of Λ = 700 MHz.

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 200MHz higher than the filter frequency. Fig.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 a time scale that is determined by the external cavity delay time. At the same time the measurements on PDB (see Fig.1) did not show any evidence of oscillatory behaviour of the power. The only power variations detected were noise-like and they are responsible for the irregular amplitudes of the signal in Fig.2.

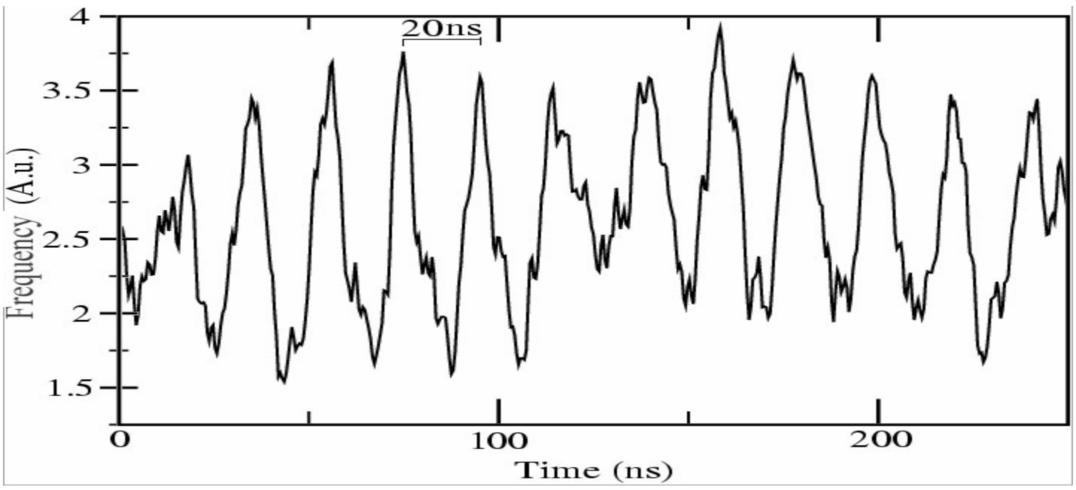

Fig. 2. Experimentally observed time series showing oscillations in the frequency of the laser when subject to filtered optical feedback. The period of the oscillations corresponds to an external delay of 6m (~20 ns).

The period of the frequency modulation signal was also measured as a function of the external cavity length. The result is shown in Fig. 3, which demonstrates the proportionality of the period of frequency oscillations to the external cavity round trip time. This linear dependence confirms that these frequency dynamics are feedback-delay-induced and that for these dynamics the RO's play a marginal role, if any. Note that such frequency oscillations do not arise for wide filters since the dynamics are then dominated by RO. Narrow filters also do not permit such frequency oscillations because the filter will effectively block the feedback for oscillations at frequencies higher than its bandwidth [5]

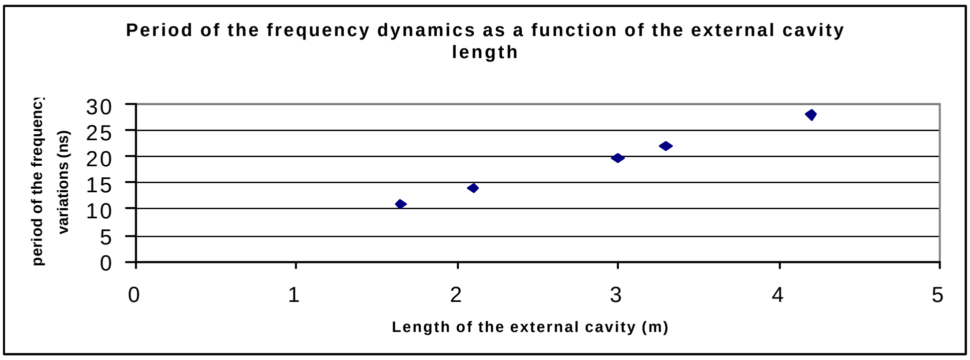

Fig. 3. Experimentally measured period of the laser frequency oscillations as a function of the external delay, showing the linear dependence of the period on the delay.

In summary, we have experimentally demonstrated novel type of oscillations in the frequency of a semiconductor laser, subject to frequency filtered external optical feedback. A judicious choice of the filter bandwidth and the detuning allowed us to produce frequency dynamics on the time scale of the external cavity roundtrip time, while the power variations remained below the detection limit. It can be shown that these types of dynamics only occur in the presence of a filter in the external cavity [6] and that these oscillations are different from the so-called Petermann-Tager oscillations [7], where both power and frequency oscillate on the external cavity roundtrip time scale. Our measurements also show that the period of the oscillations scales with the external cavity size. Such a device is an *all-optical analog* of electronic voltage-controlled oscillators (VCOs) and may find many applications.

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