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Dynamics and Synchronization Phenomena in Delay-Coupled Laser Systems

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Abstract– Semiconductor lasers are known to be very sensitive to external feedback, as well as to input from other lasers. This sensitivity, due to the nonlinear interaction of lasing field and semiconductor medium and the unavoidable delays in feedback and coupling, often results in emerging complex behavior. At the same time these nonlinear interactions lead to synchronization phenomena. For a long time such behavior has been considered undesired and difficult to treat experimentally and theoretically. Recently, tools to treat these systems have been developed, coupled lasers are serving as test-bed systems for delay-coupled networks and suggestions for applications have been proposed. In this presentation we provide examples of the advances and discuss the perspectives of such systems.

1. Introduction

Semiconductor lasers with delayed optical feedback and delayed coupling have received considerable attention from different communities, since they serve as test-bed systems for delay dynamical systems in general. Originally, the complex dynamical behavior in the emission intensity, induced by even weak optical feedback, was considered a nuisance in optical communication and storage systems, since it is reducing the signal to noise ratio. More recently, the complex dynamics has been identified to be attractive for applications, e.g. for random number generation [1] and rainbow refractometry [2]. From the fundamental dynamical point of view, many dynamical phenomena have been studied based on this configuration and could be realized experimentally with high control [3]. For all the above-mentioned aspects, a thorough understanding of the dynamical properties of semiconductor lasers with delayed feedback is of great importance. When coupling semiconductor lasers with each other, the delay in the coupling gives rise to instabilities, as well as to the possibility of different types of synchronization among the emitted intensities. The characterization and understanding of the synchronization phenomena and of the stability of the synchronization are key to their application, like e.g. chaos communication encryption schemes [4].

2. Characterizing delayed feedback instabilities

In semiconductor lasers, intensity and frequency dynamics are closely linked to each other, due to the strong coupling of amplitude and phase coupling. Therefore, in order to study delay-induced dynamical instabilities, both, amplitude and phase information are required to obtain satisfactory insight into the phase space dynamics and to understand the mechanisms involved [5]. Detection of the intensity dynamics in real-time with high bandwidth has already been possible [6,7]. It was used for investigations of phenomena like low frequency fluctuations and coherence collapse. The equally important dynamics in frequency has, however, not been accessible experimentally. For a detailed experimental characterization of the dynamical behavior, it is therefore desirable to record the amplitude and instantaneous frequency of the optical emission simultaneously. In numerical modeling this information is often extracted in form of the average frequency f, defined by the change in phase $\Phi(t)$ over one delay τ_D as $f = [\Phi(t) - \Phi(t-\tau_D)]/(2\pi\tau_D)$. Previous experiments characterizing the frequency dynamics were limited in temporal resolution or timetrace length. In such works, the spectral dynamics was reconstructed in a time averaged fashion, or the emission frequencies were obtained based on comparison with numerical modeling. We present a heterodyne detection scheme combined with a sliding Fourier transform (sFFT) analysis of the detected heterodyne timetraces to extract the frequency dynamics with nanosecond time resolution.

Figure 1 shows a scheme of the setup of the experiment. We realize the delayed feedback laser using fiber-optical components, making the setup stable and versatile.

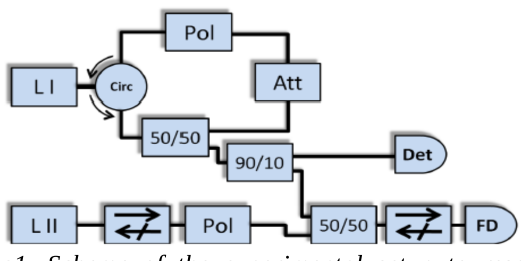

Fig1. Scheme of the experimental setup to resolve the frequency dynamics of a delayed feedback laser.

The delayed feedback laser (LI) is an Eblana fiberpigtailed discrete mode laser without integrated optical isolator. The laser is coupled to a fiber loop with an optical circulator (Circ) directly attached to the fiber-pigtail of the laser. Via a 50/50 two-by-one optical splitter (50/50) we reinject about 50 % of the power within the fiber back into the feedback loop. Using an optical attenuator (Att), we can control the feedback strength. A polarization controller (Pol) within the feedback loop allows for polarization alignment between optical feedback and emission of LI. The optical intensity coupled out from the feedback loop is used for signal detection.

We also employ a semiconductor laser as reference laser (LII), positively detuned in frequency from the delayed feedback laser. The reference laser is chosen such that its linewidth is below 1 MHz, sufficient for measuring the dynamics with high resolution. The reference laser (LII) is directly connected to an optical isolator, suppressing undesired optical feedback. The optical polarization of LII is aligned to match the one of LI using another polarization controller. The heterodyne signal, created by optical interference of LI and LII on the fast photo diode (PD), is recorded with an analog bandwidth of 16 GHz.

The dynamics of the laser frequency have been obtained by applying a sliding FFT. We continuously move a window across the entire heterodyne timetrace, calculating optical snapshot spectra for each time window. Due to the nature of the sliding FFT, temporal and spectral resolution cannot be chosen independently. We chose a time window of 4 ns length, allowing for a resolution of 125 MHz. From the snapshot spectra, we can define the instantaneous frequency of the laser as the maximum of the corresponding snapshot spectrum. Figure 2 depicts the time resolved intensity and optical frequency dynamics of LI while it was driven 3 % above the solitary laser threshold current. Under these conditions, the optical

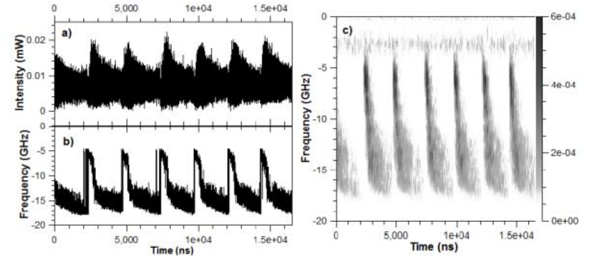

Fig2. Dynamics of a semiconductor laser with delayed optical feedback. a) intensity dynamics of LI. b) dynamics of the peak spectral component. c) dynamics of the entire emission spectrum.

emission, as shown in Fig. 2 a), displays low frequency fluctuations (LFF) with its characteristic fast intensity pulsations [6]. In Fig. 2 b), one can identify the corresponding drifts in frequency towards the high gain region (~ 13 GHz). At an intensity dropout, the emission jumps back towards a region close to the solitary laser mode (~ 3.4 GHz). From there it re-starts its drift towards the high gain region, visiting a large number of external cavity modes. Intensity and frequency traces agree with the standard observations and interpretations of LFFs [5]. Besides the maximum frequency, also the full spectrogram of the frequency dynamics can be determined, as depicted in Fig. 2 c). At any moment the emission exhibits a spectral width corresponding to several GHz. This reflects the bandwidth of the irregular picosecond pulsations. Therefore, the time-dependent spectrograms contain significantly more information than the commonly plotted average frequency f. Altogether, the real-time extraction of the frequency dynamics, depicted in panels b) and c), allows for an accurate reconstruction of how the trajectory moves along the ECMs of the mode ellipse [5]. Furthermore, it opens perspectives for the characterization of coupled lasers and other configurations in which semiconductor lasers exhibit complex dynamics, as well as for tailoring the dynamics for applications.

3. Synchronization of delay-coupled lasers

When coupling semiconductor lasers with each other, the delayed coupling also induces instabilities and in addition gives rise to different types of synchronization phenomena among the emitted intensities. The characterization and understanding of the synchronization phenomena and of the stability of the synchronization are crucial for applications, like e.g. chaos communication encryption schemes [4] and key exchange protocols [8]. For the latter scheme, two lasers have been delay-coupled via a passive relay element, in particular a semitransparent mirror. The concepts of these applications rely on synchronization of the coupled lasers, therefore, much effort has been devoted to the observation and quantification of chaos synchronization. It has, e.g. been shown, that symmetric values of coupling and feedback strengths and delay times favor synchronization [9,10]. Studies that investigate the mechanisms behind the loss of synchronization are, however, rare, particularly from an experimental perspective. Even when the linear stability analysis predicts stable synchronization, irregular escapes from the synchronized states are possible due to so-called bubbling events that are induced by noise and/or parameter mismatch. They can be attributed to transversely unstable periodic orbits embedded in the stable synchronization manifold [11,12]. The local instability forces the system's trajectory to temporarily leave the synchronization manifold until resynchronization occurs. In this contribution we present experimental studies of two delay-coupled semiconductor lasers coupled via a fiber-optic loop as passive relay.

The fiber-based setup again consists of two discrete mode semiconductor lasers (Eblana Photonics), operating at a nominal wavelength of λ~1540 nm and coupled symmetrically via a relay fiber loop. The loop has a similar effect than a semitransparent mirror, resulting in symmetric feedback and coupling with equal delay times. This coupling configurations leads to chaotic behavior in both lasers, as well as to isochronal synchronization of their outputs. Due to a 50/50 optical coupler used to combine both laser outputs in the loop, feedback and coupling strengths are identical with respect to each other. The low asymmetries in the coupling provides near-optimal synchronization conditions [9,10]. The feedback and coupling delays in our experiment account for $\tau = 73$ ns. The chosen coupling strengths are sufficiently large to avoid the regime of transverse instability due to a blow-out bifurcation [12].

Nevertheless, the maximal cross-correlation of the two lasers, obtained at zero-lag, monotonously decreases for increasing injection current, while the synchronization error increases. Figure 3 depicts the cross-correlation, the fraction of the sliding cross-correlation above a threshold of $C_{thr} = 0.5$, and the mean integrated synchronization error, versus the pump current of the two lasers.

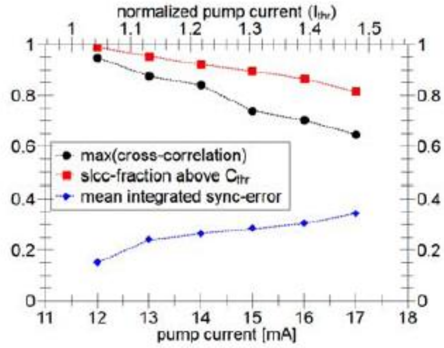

Fig3. Cross-correlation at zero-lag (black circles), fraction of the sliding cross-correlation above the correlation threshold of $C_{thr} = 0.5$ (red squares), and mean integrated synchronization error (blue diamonds), versus the pump current of the two lasers.

While similar effects have been observed in different coupling configurations, the origin of it has been so far unclear. With our setup we are able to clarify the mechanism via analysis of the time-resolved intensity dynamics. First of all, we are able to achieve high-quality zero-lag synchronization, as shown in the high-resolution time traces in Figure 4, corresponding to the coherence collapse regime. The plot depicts near-perfect synchronization, however, for a period of about 2 ns synchronization gets lost, as indicated by the double-arrow. This represents a characteristic bubbling event. Overall, in our highly resolved measurements we could reveal general differences between the synchronization dynamics of the low-frequency fluctuation at low pump currents and the coherence collapse dynamical regimes at somewhat higher pump currents. Applying the sliding cross-correlation analysis, we have systematically identified and characterized the bubbling events. Such bubbling events could be identified as the origin for the decline of synchronization with increasing current [13]. In particular, the desynchronization events become more frequent in the transition from LFF to the CC regime. Nevertheless, the synchronized intervals in between maintain their high correlation levels. It is important to note that excursions away from the synchronization manifold are detrimental to all application schemes relying on synchronization. This applies especially to communication based on synchronized chaotic carriers, as well as key exchange applications. Noise-induced desynchronization events will strongly affect the performance of bidirectional schemes and therefore must be taken into consideration when designing such concepts. Our results are thus crucial for future studies of these chaos synchronization-based applications.

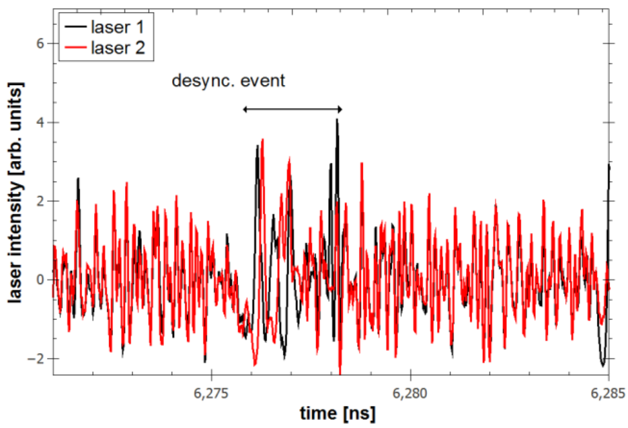

Fig4. Experimental time series of synchronized intensity dynamics in the coherence collapse regime for a pump current corresponding to $1.25I_{thr}$. A short desynchronization (bubbling) event is indicated.

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